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	Patents ADP number *(if you know it)*	6669113001
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4.	Title of the invention	REFLECTIVE LIQUID CRYSTAL DEVICES
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REFLECTIVE LIQUID CRYSTAL DEVICES

The present invention relates to reflective liquid crystal devices and more particularly to reflective liquid crystal display devices comprising a bistable twisted nematic (BTN) liquid crystal.

Reflective liquid crystal devices typically comprise a linear polariser and a mirror, with one or more retarders and a switchable liquid crystal element sandwiched between the polariser and the mirror. In a first state of the liquid crystal element, linearly polarised light passing through the polariser is reflected from the mirror and arrives back at the polariser with the same linear polarisation. Hence the reflected light is transmitted by the polariser and the device appears in the bright state. In a second state of the liquid crystal element, linearly polarised light is converted to have a circular polarisation such that upon reflection at the mirror the "handedness" of the circular polarisation is changed (i.e. from right to left or from left to right). Light arriving back at the polariser is arranged to have a polarisation angle 90° shifted from the axis of the polariser. Hence, the reflected light is not transmitted by the polariser and the device appears in the dark state. Reflective liquid crystal devices are attractive particularly for low power consumption applications.

GB9622733.5 describes a reflective liquid crystal display device comprising a polariser and a mirror between which are disposed several retarders. One of the retarders is a liquid crystal element whose optic axis is switchable so as to switch the device between a reflective state and a non-reflective state.

EP0018180 describes a liquid crystal cell comprising a cholesteric liquid crystal. The liquid crystal is bistable and can exist in either one of its two metastable states until specific steps are taken to cause a transition to the other metastable state. Energy is expended only when a transition occurs.

The article "Bistable Twisted Nematic Mode with One Polariser for Reflective Liquid Crystal Displays", Kim, Yu & Lee, IDRC Asia Display 98, Seoul, Korea, p 763, describes a device having in sequence an input linear polariser, a quarter wave retarder, a BTN element, and a mirror.

The article "Reflective Bistable Twisted Nematic Liquid Crystal Display", Xie & Kwok, Jpn J. Appl. Phys, Vol37, part 1, No. 5a (1998), p 2572, describes a device having an input polariser, a BTN mode and a reflector. The proposed device does not include any additional retarders.

WO98/48320 describes a reflective liquid crystal display device comprising a polariser and a mirror between which are disposed a half wave retarder, a quarter wave retarder, and a liquid crystal element.

Abstract 39.3 (published in the SID 1999 International Symposium, Seminar & Exhibition -Advance program, conference to be held in San Jose, CA, USA, May 16-21 1999) titled "Reflective Single-Polariser Bistable Nematic LCD with Optimum Twist", Y.J. Kim & J.S. Patel, describes a single-polariser reflective LCD having a bistable twisted nematic mode. The twist angles of the two bistable states are 63.6° and 423.6°.

According to a first aspect of the present invention there is provided a reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising two retarders, and a reflector, wherein a first of said retarders provides a retardation of substantially $m\lambda/2$ and a second of the retarders provides a retardation of substantially $n\lambda/4$ where m is an integer and n is an odd integer, and wherein at least one of the said first and second retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between a first state in which the retarder provides a retardation of substantially $m\lambda/2$ or $n\lambda/4$ and a second state in which the retardation is substantially zero.

The wavelength λ is an operating wavelength of the reflective liquid crystal device and lies in the visible spectrum and is preferably in the range 420-600nm. More preferably, the operating wavelength is in the range 440-550nm. Most preferably λ is approximately 550nm.

Preferably, the retarder comprising a BTN liquid crystal providing a retardation of $n\lambda/4$.

According to a second aspect of the present invention there is provided a reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising at least three retarders, and a reflector, wherein at least one of said retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between first and second retardation states.

The wavelength λ is an operating wavelength of the reflective liquid crystal device and lies in the visible spectrum and is preferably in the range 420-600nm. More preferably, the operating wavelength is in the range 440-550nm. Most preferably λ is approximately 550nm.

Preferably, the retarder comprising a BTN liquid crystal providing a retardation in said first state of substantially $m\lambda/2$ or $n\lambda/4$ where m is an integer and n is an odd integer, and a retardation in said second state of substantially zero. The others of said retarders may provide a retardation of substantially $m\lambda/2$ or $n\lambda/4$.

For a better understanding of the present invention and in order to show how the same may be carried into effect reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 Reflectance VS wavelength - maximum luminance attainable by the system;

Figure 2 Reflectance VS wavelength - minimum luminance attainable by the system;

Figure 3 Two layer BTN configuration in reflection described in Example 1(a);

Figure 4 Luminous reflectance VS wavelength plot for the configuration shown in Figure 3, untwisted dark state;

Figure 5 Two layer BTN in reflection configuration described in Example 1(b);

Figure 6 Luminous reflectance VS wavelength plot for the configuration shown in Figure 5, untwisted dark state;

Figure 7 Two layer BTN in reflection configuration described in Example 2;

Figure 8 Luminous reflectance VS wavelength plot for the configuration shown in Figure 7, low twist dark state;

Figure 9 Luminous reflectance VS wavelength plot for the configuration shown in Figure 7. A retarder and LC thickness reduction of 0.3 provides the improved contrast;

Figure 10 Two layer BTN in reflection configuration with an internal retarder described in Example 3;

Figure 11 Luminous reflectance VS wavelength plot for the configuration shown in Figure 10, untwisted dark state;

Figure 12(a) Two layer BTN in reflection configuration described in Example 4(a);

Figure 12(b) Two layer BTN in reflection configuration described in Example 4(b);

Figure 12(c) Two layer BTN in reflection configuration described in Example 4(c);

Figure 13 Luminous reflectance VS wavelength plot for the configuration shown in Figure 12(a);

Figure 14 Luminous reflectance VS wavelength plot for the configuration shown in Figure 12(b);

Figure 15 Luminous reflectance VS wavelength plot for the configuration shown in Figure 12(c);

Figure 16 Two layer BTN in reflection configuration described in Example 5, θ_1 varied;

Figure 17 Luminous reflectance values of the dark states given by the high twist metastable state, $\phi\pm360°$ (ϕ=twist of low twist metastable state), as a function of θ_2 (from 0° to 360°).;

Figure 18 Contrast plot obtained as a function of θ_1 (orientation angle of the retarder to the polariser, see Figure 16) from 0° to 90°;

Figure 19 Luminous reflectance VS wavelength plot for θ_1=6°, Example 5;

Figure 20 Luminous reflectance VS wavelength plot for θ_1=84°, Example 5;

Figure 21 Two layer BTN in reflection configuration described in Example 6, d, θ and ϕ are varied;

Figure 22 Table of twisted LC configurations for which LC behaves equivalent to an untwisted ¼ wave plate, (θ = angle of the input director of LC with respect to the incident linear polarisation direction, ϕ = twist of LC layer, $\Delta nd/\lambda$ specifies the required $\Delta nd/\lambda$ for which the LC device behaves like a ¼ wave plate retarder).

Figure 23 Contrast plot as a function of $\Delta nd/\lambda$, for each d the optimum θ and ϕ are found;

Figure 24 Luminous reflectance VS wavelength plot for $\Delta nd/\lambda=0.25$, d=2.007μm, Example 6;

Figure 25 Three layer BTN in reflection configuration described in Example 7;

Figure 26 Luminous reflectance VS wavelength plot for configuration shown in Figure 25. Untwisted state provides the dark state;

Figure 27 Three layer BTN in reflection configuration described in Example 8, d=4.015μm;

Figure 28 Luminous reflectance VS wavelength plot for configuration shown in Figure 27. Untwisted state provides the dark state.

Figure 29 Three layer BTN in reflection configuration described in Example 9., d=2.007μm;

Figure 30 Luminous reflectance VS wavelength plot for configuration shown in Figure 28. Untwisted state provides the dark state;

Figure 31 Three layer BTN in reflection configuration described in Example 10, d=2.564μm;

Figure 32 Luminous reflectance VS wavelength plot for configuration shown in Figure 31. Untwisted state provides the dark state; the bright state $\phi+180°$ twist state and $\phi\pm360°$ twist states are also plotted;

Figure 33 Luminous reflectance VS wavelength plot for configuration shown in Figure 34. High twist state provides the dark state;

Figure 34 Three layer BTN in reflection (achromatic) configuration described in Example 11, d=2.007μm;

Figure 35 Three layer BTN in reflection (achromatic) configuration described in Example 12. The LC orientation θ and twist φ are determined for different thickness LC layers. High twist state provides the dark state;

Figure 36 Contrast plot shown as a function of $\Delta nd/\lambda$, for each d the optimum θ and φ are found;

Figure 37 Luminous reflectance VS wavelength plot for $\Delta nd/\lambda=0.25$;

Figure 38 Luminous reflectance VS wavelength plot for $\Delta nd/\lambda=0.72$; and

Figure 39 Luminous reflectance VS wavelength plot for $\Delta nd/\lambda=0.536$.

A Bistable Twisted Nematic (BTN) mode used in a reflection configuration requires one of its two metastable states, i.e. addressable states (φ & φ±360°), to provide a dark state and the other a bright state. A single retarder layer (i.e. BTN only) does not provide a good achromatic dark state. Configurations involving several retarder layers are required when seeking good achromatic dark states which switch to good bright states. Additionally, the likelihood of the undesired stable state φ±180° nucleating into an addressed pixel means that its optical appearance (luminance, colour co-ordinates, etc.) may be of importance. It has been found that the stable state φ±180° bears a closer resemblance to the high twist metastable state than the low twist (or untwisted) metastable state. This suggests that the high twist state should be used as the background state (i.e. normally bright mode or normally dark mode depending on the configuration), so that if the undesired state nucleates it will appear similar to the

background. There is currently no clear advantage to choosing a normally bright over a normally dark mode in a storage reflection device.

In addition to the bright, high contrast requirements for reflection displays, the thickness of the LC layer has to be compatible with fabrication purposes, i.e. not too thin. A low birefringence (Δn) LC material provides a thicker LC layer, though it is also possible to increase the LC layer thickness by introducing a small amount of twist into the layer to compensate for the extra thickness (this slightly modifies the resulting optics).

Various BTN mode configurations were investigated by theoretical modelling for their use in reflection displays. Being a reflective display the luminous reflectance of the bright state will depend on the light source utilised. In the examples given below, a CIE standard illuminant D-65 was used. Realistic values were used in modelling the various components, i.e. LC, polariser, retarders and aluminium reflector. The low birefringence ($\Delta n \sim 0.0685$) liquid crystal MJ96538 (Merck Japan) was used in zero surface tilt configurations (introducing a surface tilt modifies the results slightly).

The maximum contrast ratio ($CR = L_{MAX}/L_{MIN}$) attainable for a single polariser system modelled with the above elements was calculated to be 168.8 (where the maximum luminance ($L_{MAX}=0.34941$) was calculated for a single polariser and reflector configuration with no LC, and the minimum luminance ($L_{MIN}=0.00207$) was calculated by adding a perfect (theoretical) quarter-wave retarder (i.e. quarter wave at all wavelengths) between the polariser and reflector at 45° to the transmission axis of the polariser). The luminous reflectance curves for these maximum (bright state) and minimum (dark state) luminances are shown in Figures 1 and 2. The dark state is very achromatic in behaviour while the bright state is governed by the "shape" of the D65 light source.

The embodiments of the invention to be described aim to obtain high contrast in reflection in various BTN configurations by means of achromatic dark states (dark over a wide range of wavelengths, preferably covering all the visible range) which switch to

good bright states. Achromaticity of the dark and bright states is desired so that the display does not appear coloured.

The following configurations are typically examples of the LC layer acting as a switchable retarder located adjacent to the reflector. This set up aids fabrication purposes, i.e. no internal retarders are required in the device as they can be located externally. Two and three layer configurations are investigated. In most of the embodiments discussed, the LC can be substituted for any of the other retarder elements described in the configurations so long as it adopts the correct retardation and orientation.

The configurations investigated obtain the dark state by converting linearly polarised light generated by the polariser into circularly polarised light. Where one of the BTN metastable states contributes to the conversion to circularly polarised light while the other metastable state doesn't. Upon reflection back through the system a dark and a bright state are obtained. However, it is also possible to convert the linearly polarised light from the polariser into elliptically polarised light (by altering the retarders properties, e.g. orientation and/or thickness) such that the BTN metastable states convert the elliptically polarised light to either circular or linear polarisation.

Example 1

Half-wave ($\lambda/2$) retarder + quarter-wave ($\lambda/4$) LC - untwisted dark state.

(a) Configuration shown in Figure 3: fixed half-wave ($\lambda/2$@550nm) retarder at 15° to the transmission axis of the polariser followed by a quarter-wave ($\lambda/4$) LC layer at 75° to the transmission axis of the polariser. The LC layer is 2.007μm thick. A dark state which is more achromatic than that of a single retarder layer is provided by the untwisted state, ~110nm range compared to the previous 40nm, see luminous reflectance plot in Figure 4. The bright state is the same for both the +360° and -360° twisted state giving a maximum contrast of 79.5.

(b) The half-wave ($\lambda/2$) retarder is placed at 22.5° to the transmission axis of the polariser and the LC layer at 90° to the transmission axis of the polariser, see Figure 5. The LC layer has a thickness of 2.007μm. The dark state is given by the untwisted state but both states are shown in Figure 6 to be quite chromatic. A contrast of 38.2 is obtained for such a configuration.

Example 2

Half-wave ($\lambda/2$) retarder + quarter-wave ($\lambda/4$) LC - low twist provides dark state.

In this case, both BTN states have some degree of twist as a result of using a thicker LC layer (d=2.842μm). The half-wave ($\lambda/2$) retarder is at 15° to the transmission axis of the polariser with the LC layer oriented at 30° to the transmission axis of the polariser. A twist of ϕ=63.6° is incorporated to the LC layer and provides the dark state. The higher twist states (ϕ±360°) provides the bright state of which the ϕ-360°=-296.4° provides the better bright state. A diagram of this configuration is shown in Figure 7. A contrast of 31.6 is obtained. The luminous reflectance curves shown in Figure 8 suggest that the contrast would be higher were the curves shifted to the left. This can be achieved by reducing the thickness of the retarder and LC layer. For example, reducing both their thickness by ~0.3 resulted in a contrast of 66.5, over twice the previous contrast of 31.6. The luminous reflectance curves are shown in Figure 9.

Example 3

Half-wave ($\lambda/2$) LC + internal quarter-wave ($\lambda/4$) retarder - untwisted dark state.

Configuration similar to Example 1(a) except for the LC acting as the half-wave ($\lambda/2$) retarder at 550nm oriented at 15° to the transmission axis of the polariser. The LC layer thickness is 4.015μm. A fixed quarter-wave retarder at 75° to the transmission axis of the polariser is located between the LC layer and the reflector, see Figure 10. The dark state corresponds to the untwisted state and the high twist state to the bright state, the ±360° have the same luminous reflectance. The luminous reflectance curves are shown in Figure 11. A contrast of 64.6 is obtained.

Example 4

Specific retarder + twisted LC configurations - low twist provides the dark state.

Three such solutions were investigated and are shown schematically in Figure 12, labelled (a) to (c). The LC layer is twisted through ϕ to give the dark state and the bright state corresponds to the higher twisted case ($\phi \pm 360°$). The optimum bright state was obtained for the (ϕ-360°) twist state, providing reasonable contrasts:

(a) An untwisted (Δnd=185.2nm) retarder and (Δnd=173.9nm, d=2.539μm) LC layer, are both orientated at 15° to the transmission axis of the polariser. The LC has a twist of 85.5°. This configuration gives a contrast of 86.7 and the luminous reflectances are plotted in Figure 13.

(b) The untwisted (Δnd=220.8nm) retarder is orientated at 15° to the transmission axis of the polariser and (Δnd=152.5nm, d=2.226μm) LC layer is orientated at 32.5° to the transmission axis of the polariser with an internal twist of 63.6°. The luminous reflectances are plotted in Figure 14 and a maximum contrast of 81 was obtained.

(c) The untwisted (Δnd=207.9nm, d=2.22μm) retarder is orientated at 14.2° to the transmission axis of the polariser and (Δnd=152.1nm) LC layer is orientated at 29° to the transmission axis of the polariser with an internal twist of 67°. The luminous reflectances are plotted in Figure 15 and a highest of the contrasts was obtained, contrast = 99.

Example 5

Variation of the angle between the polariser and half-wave retarder (θ_1), where the angle between the half-wave retarder and LC layer satisfies θ_2=2θ_1 (since the half-wave retarder rotates linear polarisation by 2θ_1) - low twist state provides the dark state.

This configuration is illustrated in Figure 16: half-wave retarder (at 550nm) placed between the LC layer and polariser at an angle of θ_1 to the transmission axis of the polariser and the LC layer is at θ_2 to the transmission axis of the polariser where $\theta_2=2\theta_1$. The LC layer selected to have a thickness of 2.842μm and a ±63.6° twist provides the dark state. A negative twist requires the values of θ_1 to be reversed in sign. The luminance of the dark states were calculated for both a LC layer twist of ±63.6° as a function of θ_2 from 0° to 360° (i.e. θ_1 from 0° to 180°), and the results plotted in Figure 17. The results indicate that a positive LC layer twist provides a lower luminance (better dark state) over the 0° to 90° range for θ_1 than an equivalent negative LC layer twist.

The angle θ_1 was varied between 0° and 90° and the resulting contrasts were calculated. A plot of the contrasts as a function of θ_1 for a LC layer twist of 63.6° is plotted in Figure 18. Two regions give good contrasts, $\theta_1 \approx$ 6°& 84°, respective contrasts of 50.5 and 58.9. The luminous reflectance curves for θ_1=6° are shown in Figure 19, the dark state has a high luminous reflectance at low wavelengths which lowers the overall contrast, even though at higher wavelengths the dark state looks very achromatic. An improved dark state at low wavelengths can be obtained by shifting the curves to the left by reducing the retarder and LC layer thickness. The dark state at θ_1=84° is symmetrical, see the luminous reflectance curves in Figure 20, resulting in an overall higher contrast even though the wavelength range over which it is effectively dark is the same as for θ_1=6°.

This exercise can be repeated for different retarder and LC layer thicknesses (and hence different LC layer twist) to try and improve the contrast and/or increase the LC layer' thickness.

Example 6

Fixed half-wave ($\lambda/2$) retarder + variable thickness LC layer - low twist provides dark state.

This arrangement is shown in Figure 21, a half-wave retarder (550nm) at 15° to the transmission axis of the polariser. The LC layer is placed between the retarder and reflector and the low twist state provides the dark state. The thickness of the LC layer is selected from the table of LC configurations (between $\Delta nd/\lambda=0.25$ & 0.75), see Figure 22, and for each thickness the configuration (orientation θ and twist ϕ) giving the best dark state was determined (via locating the minima on a 3-D surface plot). Figure 22 is a Table of twisted LC configurations for which the LC behaves equivalently to an untwisted ¼ wave plate, (θ = angle of the input director of LC with respect to the incident linear polarisation direction, ϕ = twist of LC layer, $\Delta nd/\lambda$ specifies the required $\Delta nd/\lambda$ for which the LC device behaves like a ¼ wave plate retarder). The contrast as a function of LC layer thickness was obtained. These contrasts are plotted as a function of $\Delta nd/\lambda$ (birefringence Δn, thickness d, wavelength λ) in Figure 23. As $\Delta nd/\lambda$ increases the contrast rapidly decreases. A maximum contrast of 89 was obtained, corresponding to a $\Delta nd/\lambda= 0.25$, d=2.007, $\theta=81$, $\phi=-11$. Its luminous reflectance curves are given in Figure 24. The (ϕ+360)° high twist state gave a higher luminance than the (ϕ-360)° high twist state.

Further improvements are possible by varying the retardation (thickness) of the fixed half-wave retarder and repeating this exercise.

Example 7

Two half-wave ($\lambda/2$) retarders + ($3\lambda/4$) LC - untwisted dark state.

Two half-wave retarders (550nm) placed at 15° and -15° to the transmission axis of the polariser with a 6.022μm LC layer at 75°, as shown in Figure 25. The untwisted state corresponds to the dark state and the high twist state gives the bright state. The resulting dark and bright states are not very achromatic, see reflectance curves plotted in Figure 26, leading to a low contrast of 20.4. Dark state has a 500-550nm wavelength range. The luminous reflectance curves (especially the 0° and -360° states) are very chromatic which may be good as a two colour display.

Example 8

Half-wave (λ/2), quarter-wave (λ/4) + (λ/2) LC - untwisted dark state.

In this case, the half-wave retarder is at 15° to the transmission axis of the polariser while the quarter-wave retarder is at -15°, see Figure 27. The LC layer has a thickness of 4.015μm and is positioned at 75° to the polariser's transmission axis. The untwisted state gives the dark state, which only has a small wavelength range. A very poor bright state is obtained from the ±360° twist state, in fact, it looks more like a very chromatic dark state as shown in the reflectance curves in Figure 28, resulting in a very low contrast of 6.1.

These two cases (Examples 7 and 8) can be seen as belonging to a more general case: (λ/2) @ ~15° + [(λ/4)+x] @ ~-15° + [(λ/2)+x] @ ~75° where x lies between 0 & λ/4.

Example 9

Two half-wave (λ/2) retarders + (λ/4) LC - untwisted dark state.

The two half-wave retarders are at 6.9° and 34.5° to the transmission axis of the polariser, as shown in Figure 29. An untwisted, 2.007μm LC layer, at 100.2° to the transmission axis of the polariser, provides a good achromatic dark state (~180nm wide), with the exception that at very low wavelengths the dark state becomes poor, see Figure 30. The high twist (±360°) state in turn gives a good bright state (though chromatic in behaviour) which leads to a contrast of 89. The dark state may be improved (possibly increasing the contrast) by decreasing the thickness of the retarders and LC layer.

Additionally, increasing the thickness of the LC layer and determining for that thickness the optimum (θ orientation and ϕ twist of LC layer) configuration, other high contrasts may be found. It could also be possible to increase the thickness of the LC layer by using the LC as one of the (λ/2) elements instead of the (λ/4) element, though this would require an internal retarder which could be fabricated by a reactive mesogen layer.

Example 10

A (23λ/72) and (λ/2) retarder + LC (23λ/72) - untwisted dark state.

A 23λ/72 retarder placed at 14.25° to the transmission axis of the polariser followed by a half-wave retarder at 84.5°. The LC is oriented at 14.25° and has a retardation of ~23λ/72 (d=2.564μm). Figure 31 gives a schematic representation. The dark state is given by the untwisted state. The bright state is obtained by the high twisted (±360°) state, though the undesired ±180° twist state gave a higher luminance than the ±360° twist state, as can be seen in Figure 32. A contrast of 55.4 is obtained.

The thickness of the LC layer could be increased by using the LC as one of the (λ/2) element instead of the (23λ/72) elements, though this again would require an internal retarder.

Example 11

Achromatic configuration + LC: (λ/2) retarder + (λ/4) retarder + (λ/4) LC layer.

This configuration is different to all the previous configurations discussed because the fixed retarder(s) provide the dark state and the LC is used to switch their effect on and off. Therefore, the high twist state gives the dark state and the low twist state gives the bright state. The high twist (±360°) states gave very similar dark states, shown in Figure 33.

The half-wave retarder is at 15° to the transmission axis of the polariser and the quarter-wave retarder and LC layer are both at 75°, as shown in Figure 34. A 2.007μm thick LC layer was used and this gave a contrast of 95.9 with a good dark state which is reasonably achromatic, except at low wavelengths. Luminous reflectance curves are shown in Figure 33.

Example 12

Achromatic configuration + LC (varying the LC layer thickness) - high twist dark state.

This configuration utilises the same half-wave/quarter-wave retarder configuration used in Example 11: the LC switches the achromatic quarter-wave configuration on and off. The LC configuration (θ and ϕ) which gave the best dark state for a given LC layer thickness was found. Repeating over a range of LC layer thickness' and therefore $\Delta nd/\lambda$. The bright states was given by the corresponding low twist state. The general configuration is represented in Figure 35. The contrasts determined were plotted as a function of $\Delta nd/\lambda$ in Figure 36. Once again, two contrast maxima are found. The highest occurs at $\Delta nd/\lambda=0.25$ (d=2.007μm, $\theta=-70°$, $\phi=-15°$) and gives a contrast of 133. Its luminous reflectance curves are plotted in Figure 37. As can be seen, a very good dark state (very achromatic) and a very reasonable bright state are obtained, though both are poor at low wavelengths. The second maxima occurs at $\Delta nd/\lambda\sim0.72$ (d=5.781μm, $\theta=3°$, $\phi=-24°$), contrast of 106. The dark state is reasonably good but the bright state is very chromatic, see its' reflectance curves in Figure 38.

An example of one of the poorer contrasts (CR=23) obtained (thickness of 4.304μm, $\theta=0°$, $\phi=-15°$) is also included. Its reflectance curves, Figure 39, show a reasonable dark state with a very poor bright state.

CLAIMS:

1. A reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising two retarders, and a reflector, wherein, in at least one state of the device, a first of said retarders acts to rotate linearly polarised light of wavelength λ and a second of the retarders acts to convert linearly polarised light of wavelength $(1 + y)\lambda$ $[0.8<y<1.25]$ to circular polarised light, and wherein at least one of the said first and second retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal.

2. A device according to claim 1, wherein the BTN is switchable between a first state in which it rotates linearly polarised light and a second state in which it does not rotate linearly polarised light.

3. A device according to claim 1, wherein the BTN is switchable between a first state in which it converts linearly polarised light to circularly polarised light and a second state in which it does not convert linearly polarised light to circularly polarised light.

4. A device according to claims 1 or 2, wherein the retarder adjacent to the polariser is a fixed retarder with optic axis at an angle θ_1 and the retarder adjacent the reflector is a BTN which in the low twist state, ϕ and has the input director (LC director at cell surface adjacent to retarder) at an angle $\theta_2 = 2\theta_1+\theta(\phi)+x$.

5. A device according to claim 4, wherein $x < 5°$, preferably $0°$.

6. A device according to claim 4 or 5, wherein θ_1 is substantially $15°$ and the low twist state is substantially $\phi = 0°$.

7. A device according to claim 4 or 5, wherein $5°< \theta_1 < 25°$ and the low twist state is substantially $\phi = 63.6°$.

8. A device according to claim 7, wherein $\theta_1 = 15°$ and the low twist state is substantially $\phi = 63.6°$.

9. A device according to claim 7, wherein $\theta_1 = 6°$ and the low twist state is substantially $\phi = 63.6°$.

10. A device according to claim 4 or 5, wherein $5° < 90° - \theta_1 < 25°$ and the low twist state is substantially $\phi = 63.6°$.

11. A device according to claim 10, wherein $\theta_1 = 84°$ and the low twist state is substantially $\phi = 63.6°$.

12. A device according to claim 1 or 2, wherein the retarder adjacent the polariser is a BTN which in the low twist state has $\phi = 0°$ and optic axis at an angle α, and the retarder adjacent the reflector is a fixed retarder with optic axis at an angle $2\alpha+45°+x$.

13. A device according to claim 12, wherein $x < 5°$, preferably $0°$.

14. A reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising two retarders, and a reflector, wherein a first of said retarders provides a retardation of substantially $m\lambda/2$ and a second of the retarders provides a retardation of substantially $n\lambda/4$ where m is an integer and n is an odd integer, and wherein at least one of the said first and second retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between a first state in which the retarder provides a retardation of substantially $m\lambda/2$ or $n\lambda/4$ and a second state in which the retardation is substantially zero.

15. A device according to claim 14, wherein the wavelength λ is an operating wavelength of the reflective liquid crystal device and is in the range 420-600nm.

16. A device according to claim 15, wherein the wavelength λ is in the range 440-550nm.

17. A device according to claim 16, wherein λ is approximately 550nm.

18. A device according to any one of claims 14 to 17, wherein the retarder comprising a BTN liquid crystal provides a retardation of $n\lambda/4$.

19. A reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising at least three retarders, and a reflector, wherein at least one of said retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between first and second retardation states.

20. A device according to claim 19, wherein the retarder adjacent to the reflector acts to convert linearly polarised light of wavelength $(1 + y)\lambda$ $[0.8<y<1.25]$ to circular polarised light, and the two other retarders act to rotate linearly polarised light of wavelength λ.

21. A device according to claim 20, wherein the retarder adjacent the polariser is at an angle α to the transmission axis of the polariser, the next retarder is at an angle β to the transmission axis of the polariser and the retarder adjacent the reflector is a BTN which in the low twist state, ϕ, and has the input director (LC director at cell surface adjacent to retarder) at an angle $2(\beta-\alpha)+\theta(\phi)+x$ to the transmission axis of the polariser.

22. A device according to claim 21, wherein $x < 5°$, preferably 0°.

23. A device according to claim 22 in which $\alpha = 6.9°$ and $\beta = 34.5°$

24. A device according to claim 19, wherein the retarder adjacent to the polariser acts to rotate linearly polarised light of wavelength λ, the middle retarder acts to convert

linearly polarised light of wavelength $(1 + y)\lambda$ $[0.8<y<1.25]$ to circular polarised light, and the retarder adjacent to the reflector is a BTN device.

25. A device according to claim 24, wherein the retarder adjacent to the polariser has optic axis at α to the transmission axis of the polariser, the middle retarder has optic axis at $2\alpha+45°$ to the transmission axis of the polariser.

26. A device according to claim 25, wherein $\alpha=15°$ and the BTN has a low twist state of 0° orientated at 75° to the transmission axis of the polariser.

27. A device according to claim 19, wherein said at least one retarder provides a retardation in said first state of substantially $m\lambda/2$ or $n\lambda/4$ where m is an integer and n is an odd integer, and a retardation in said second state of substantially zero.

28. A device according to any one of claims 20 to 27, wherein the wavelength λ is an operating wavelength of the reflective liquid crystal device and is in the range 420-600nm.

29. A device according to claim 28, wherein the wavelength λ is in the range 440-550nm.

30. A device according to claim 29, wherein λ is approximately 550nm.

31. A device according to any of the preceding claims in which the BTN switches between a state $\phi°$ and $(\phi\pm360)°$.

32. A device according to any of the preceding claims in which the BTN switches between a state $\phi°$ and $(\phi\pm180)°$.

ABSTRACT

REFLECTIVE LIQUID CRYSTAL DEVICES

A reflective liquid crystal device comprises in sequence a linear polariser, a retarder arrangement comprising two retarders, and a reflector. A first of the retarders provides a retardation of $m\lambda/2$ and a second of the retarders provides a retardation of $n\lambda/4$, where m is an integer and n is an odd integer, and wherein at least one of the first and second retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal. This BTN retarder is switchable between a first state in which the retarder provides a retardation of $m\lambda/2$ or $n\lambda/4$ and a second state in which the retardation is zero.

Figure 3

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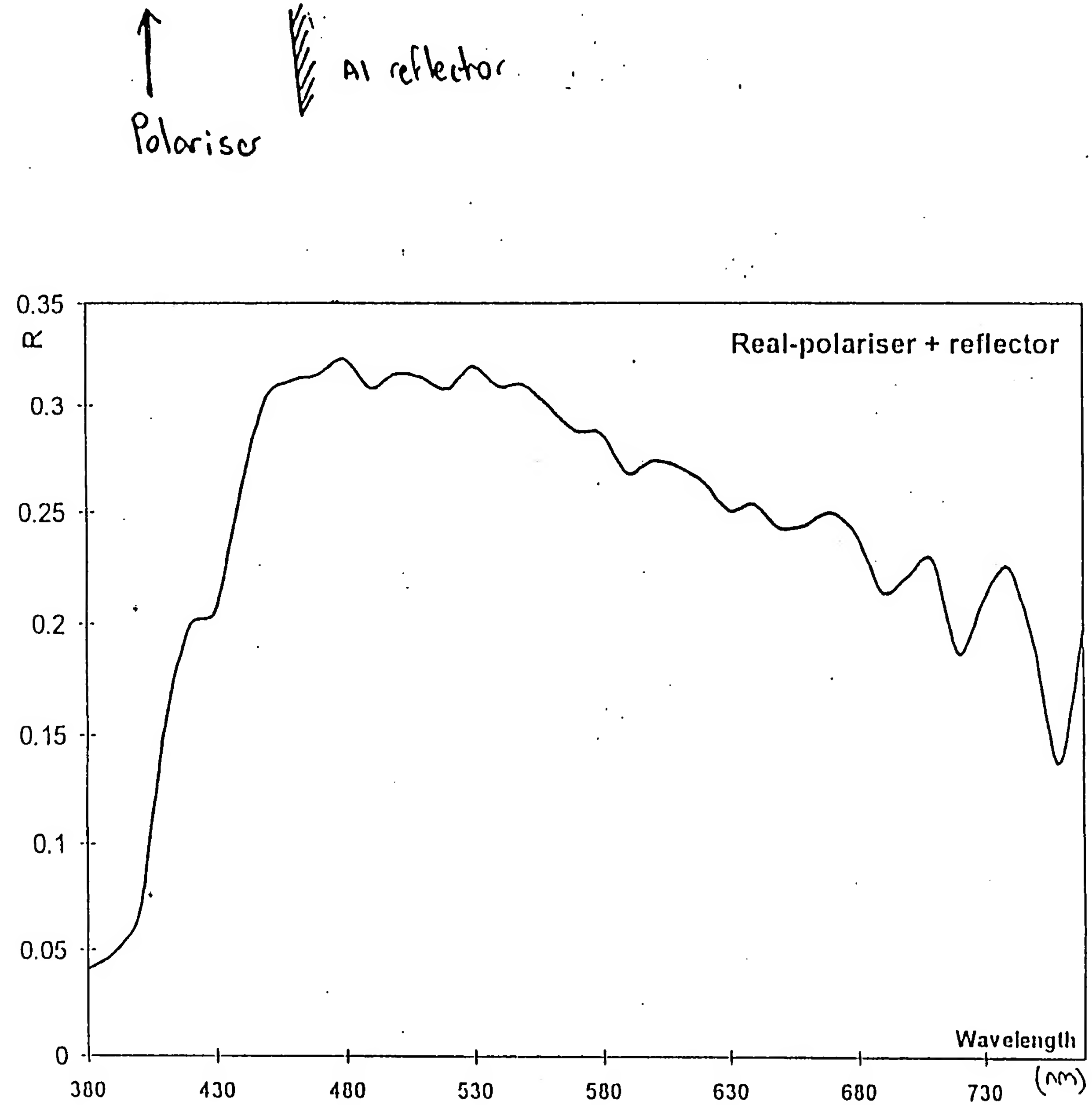
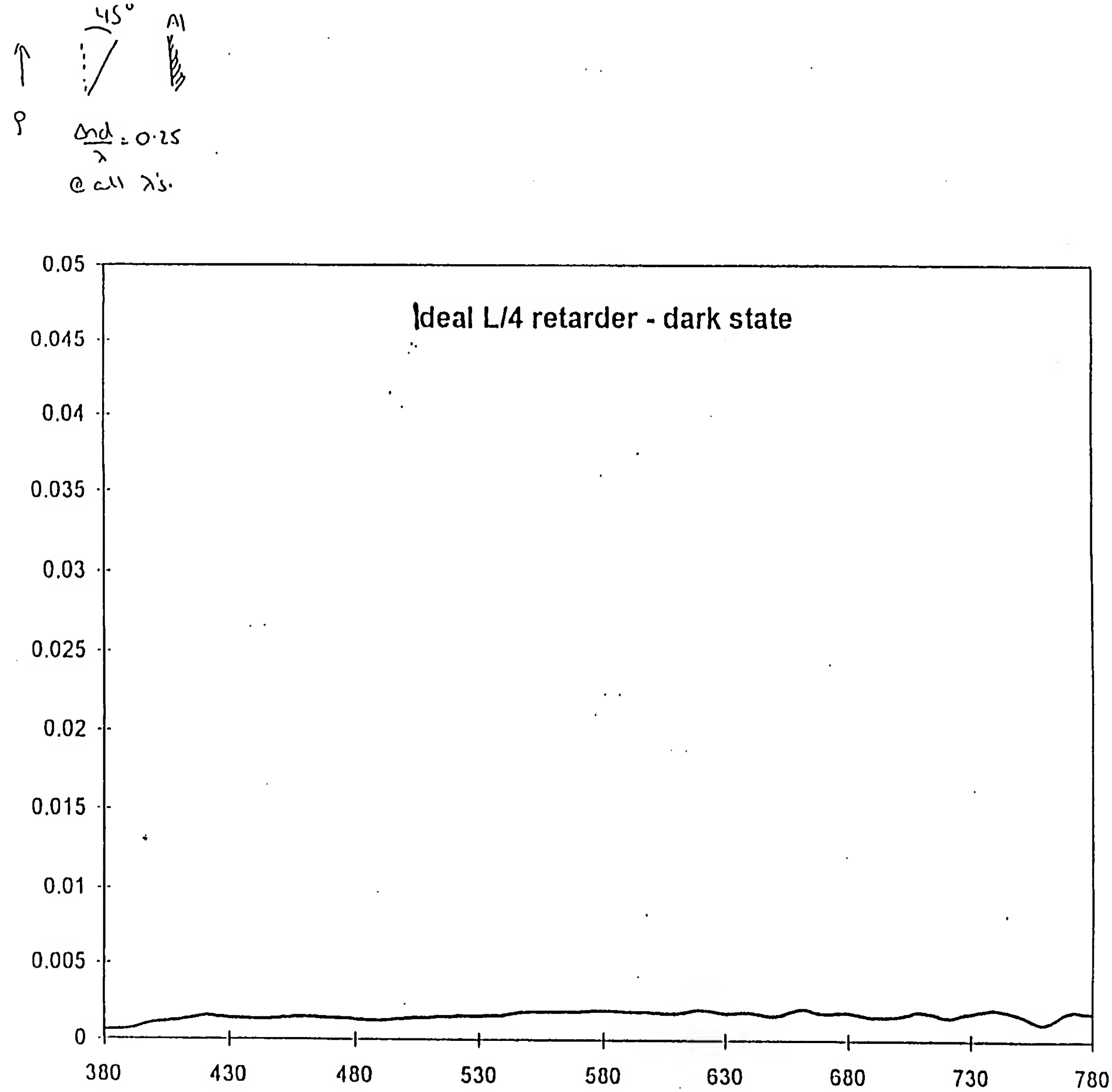


Polariser
Al reflector
R
Real-polariser + reflector
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
Wavelength
(nm)

FIGURE 1



45°
Al
P
$\frac{\Delta nd}{\lambda} = 0.25$
@ all λ's.
Ideal L/4 retarder - dark state
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
380
430
480
530
580
630
680
730
780

FIGURE 2

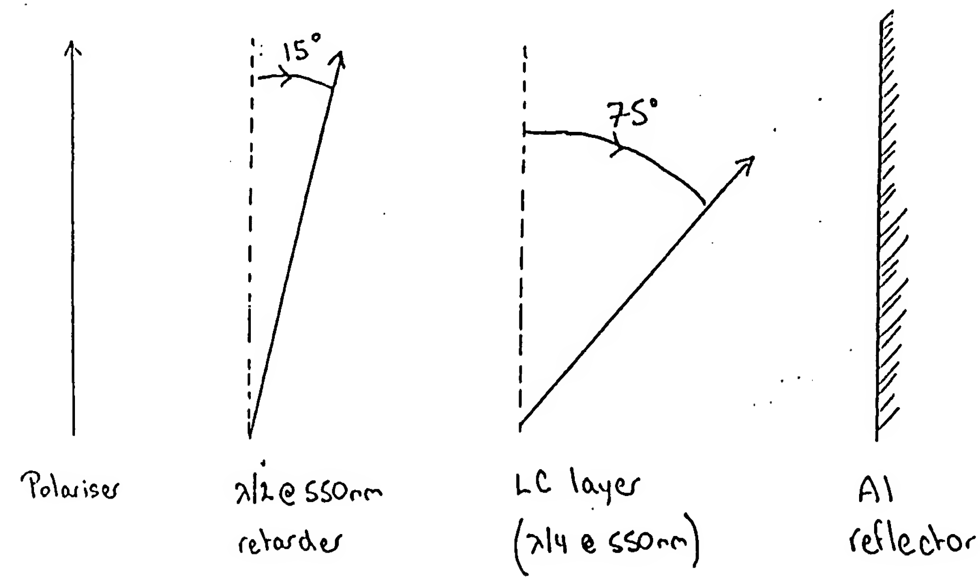
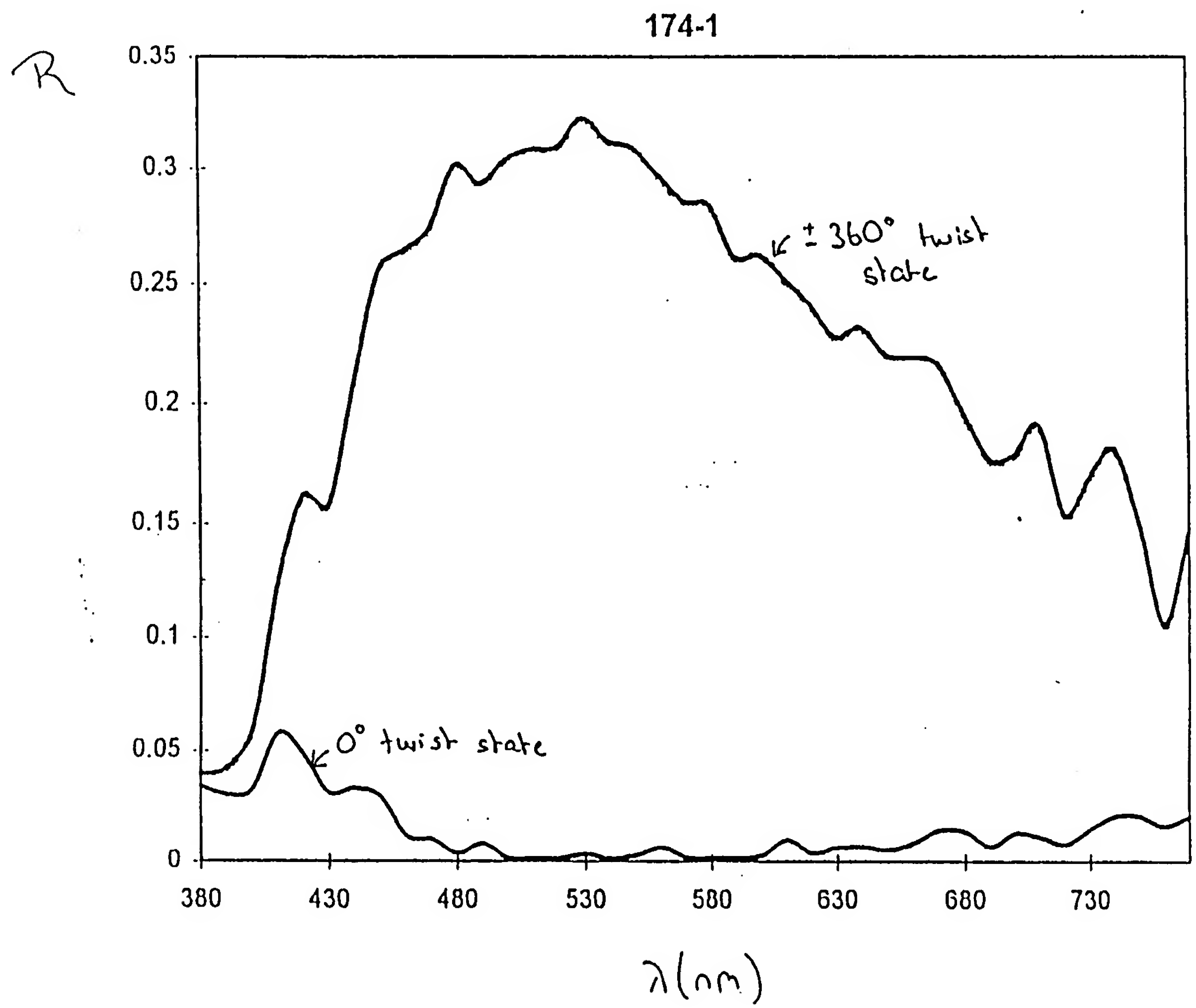

15°
75°
Polariser
λ/2 @ 550nm
retarder
LC layer
(λ/4 @ 550nm)
Al
reflector

FIGURE 3

FIGURE 4


174-1
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
$\pm$ 360° twist state
0° twist state
λ(nm)

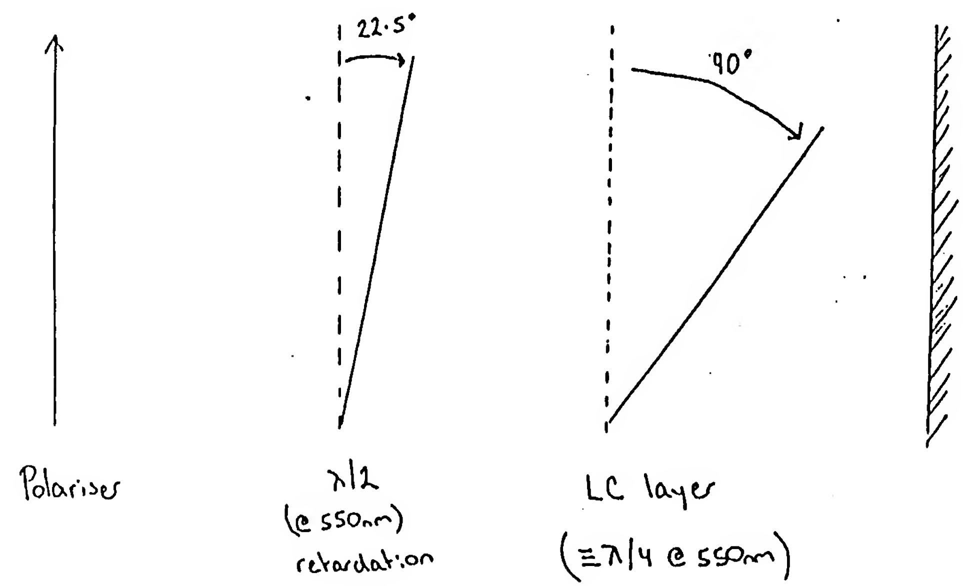


FIGURE 5

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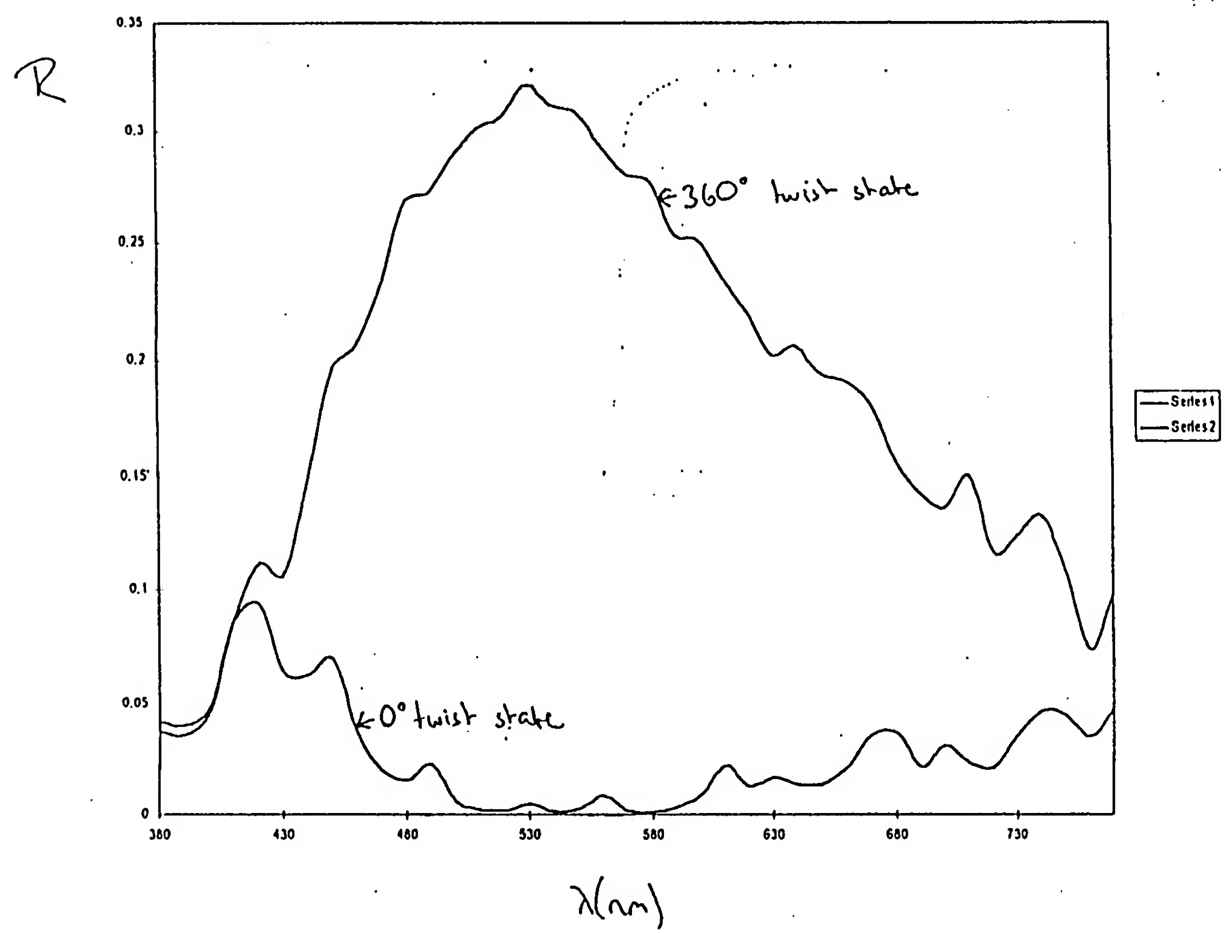
(35-2)

FIGURE 6



R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
←360° twist state
←0° twist state
Series1
Series2
λ(nm)

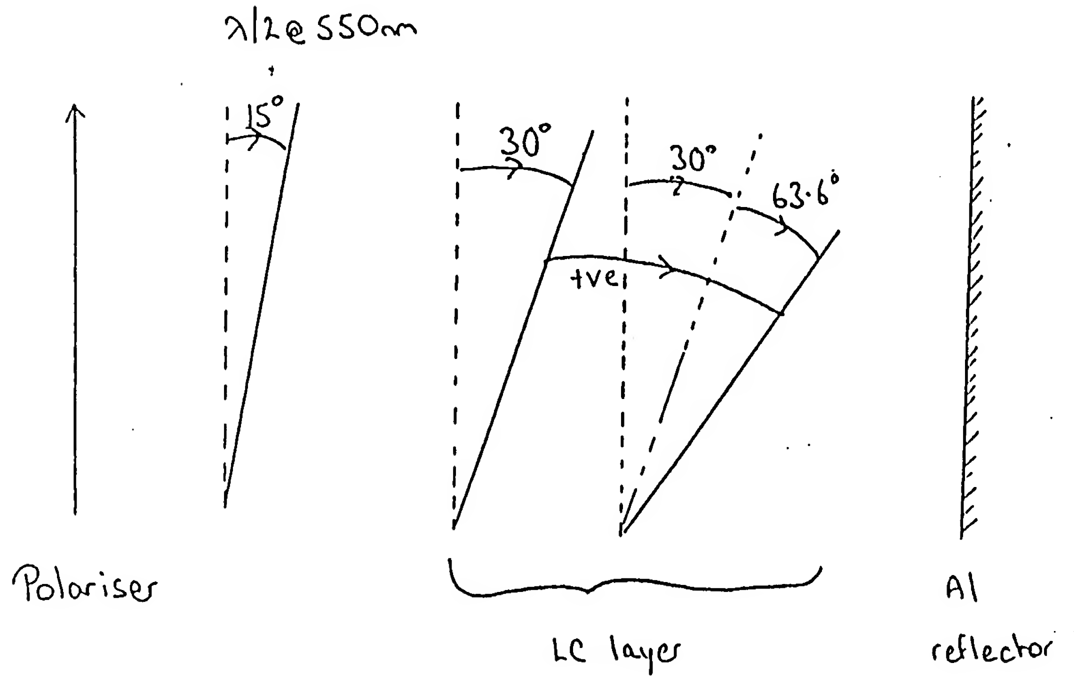


FIGURE 7

FIGURE 8

175-1

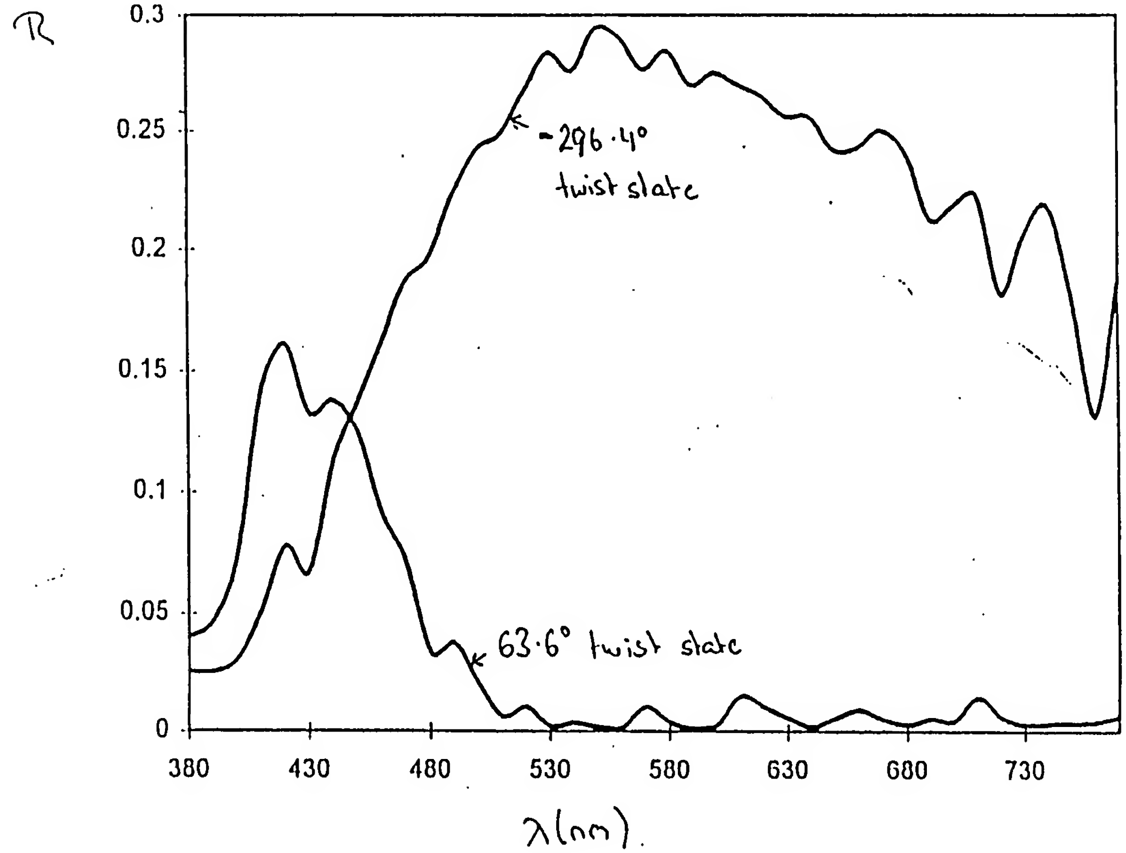
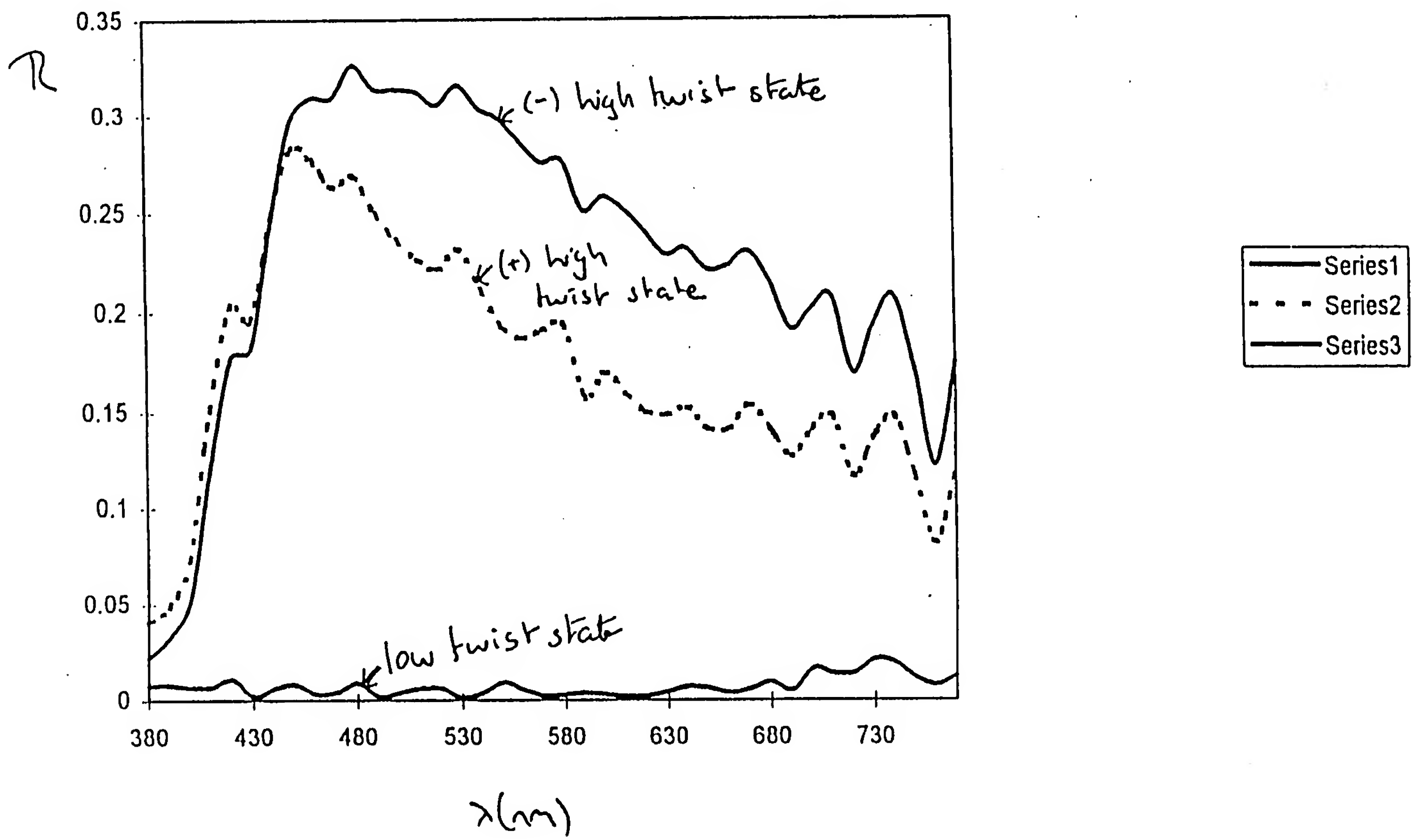


FIGURE 9


R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
λ(nm)
(-) high twist state
(+) high twist state
low twist state
Series1
Series2
Series3

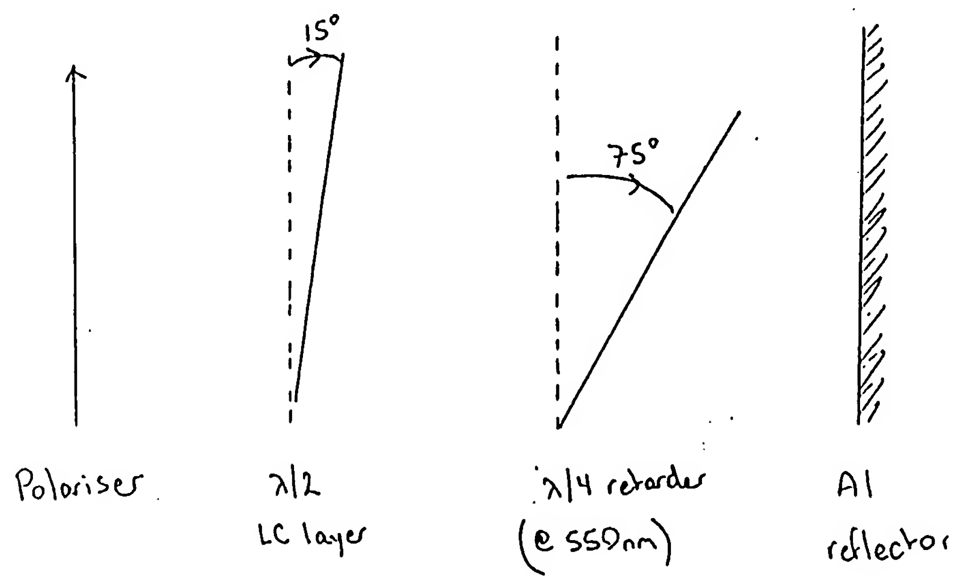


FIGURE 10

FIGURE 11

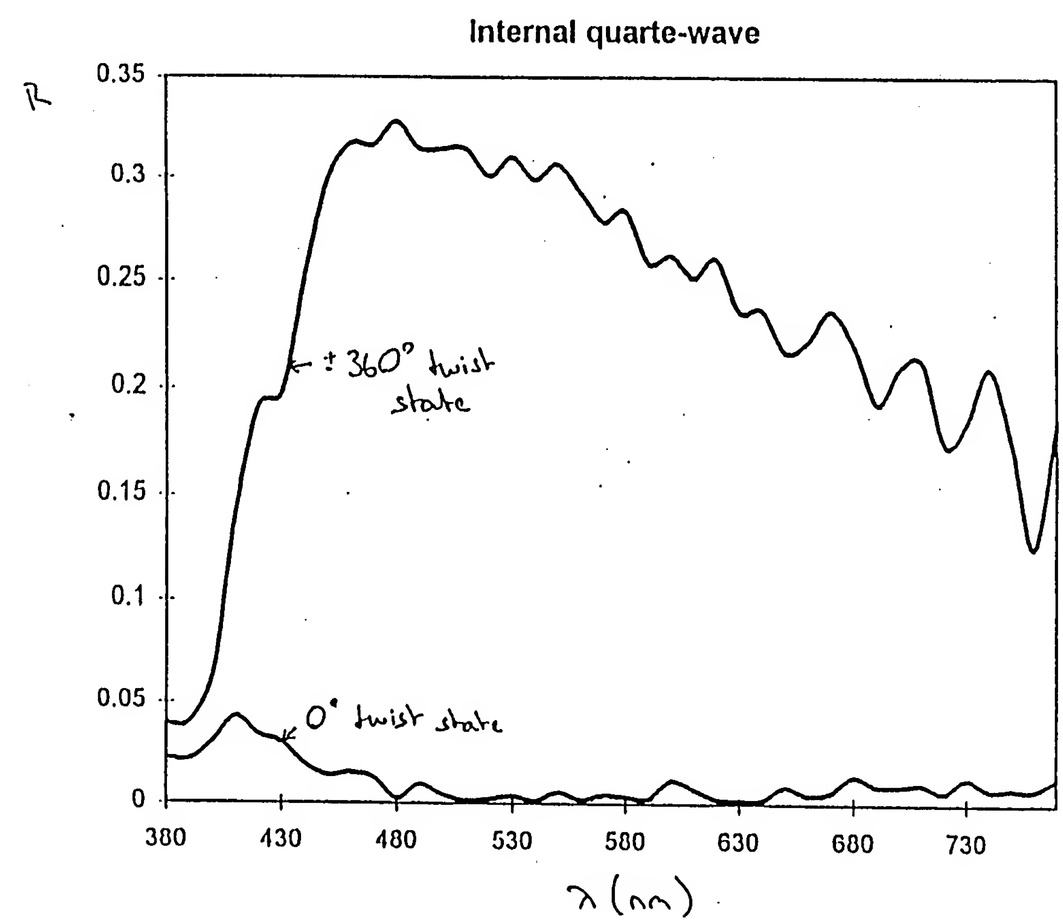

Internal quarte-wave
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
λ (nm)
± 360° twist state
0° twist state

FIGURE 12

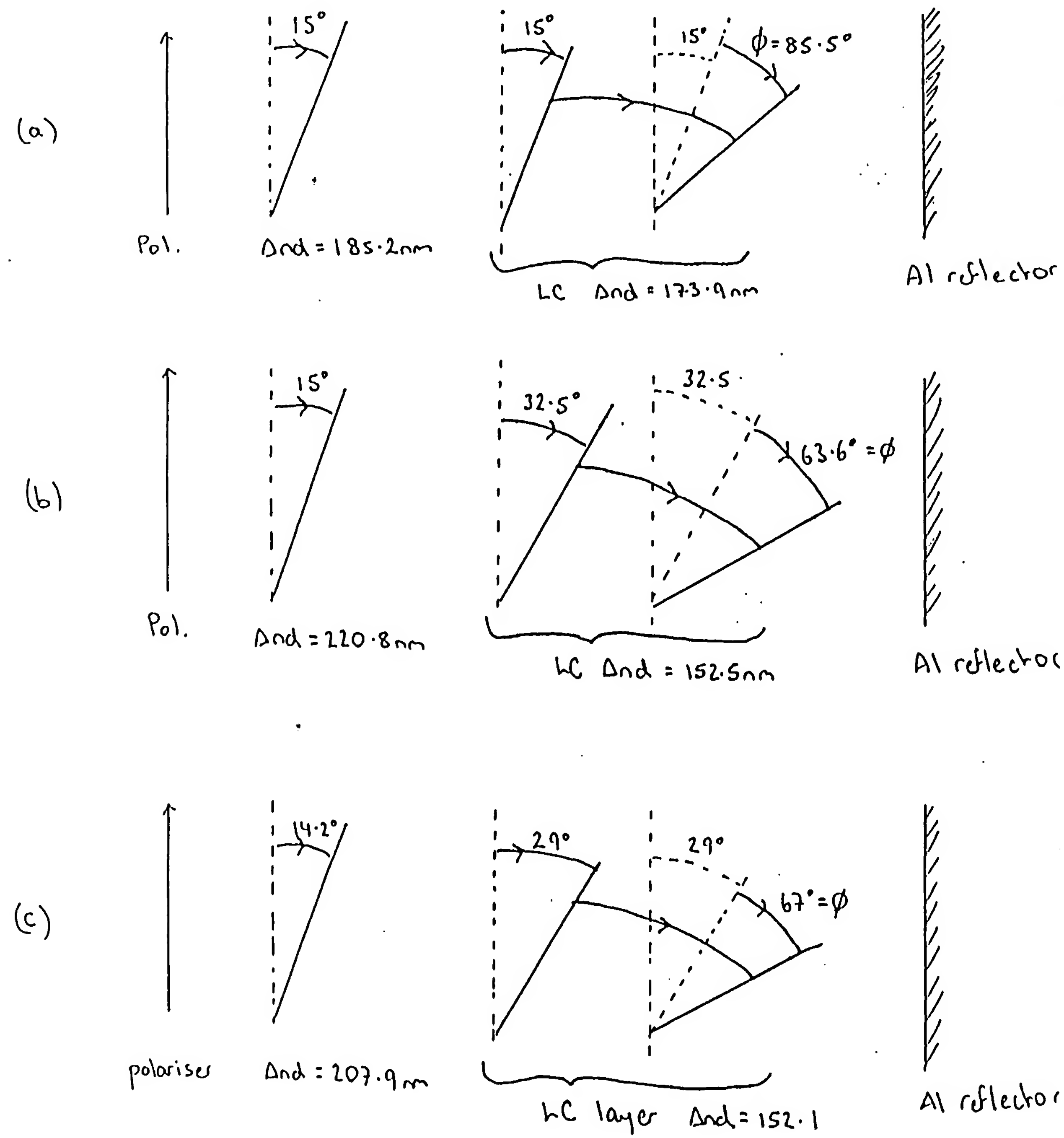

(a)
Pol.
15°
Δnd = 185.2nm
15°
15°
φ = 85.5°
LC Δnd = 173.9nm
Al reflector
(b)
Pol.
15°
Δnd = 220.8nm
32.5°
32.5
63.6° = φ
LC Δnd = 152.5nm
Al reflector
(c)
polariser
14.2°
Δnd = 207.9nm
29°
29°
67° = φ
LC layer Δnd = 152.1
Al reflector

FIGURE 13

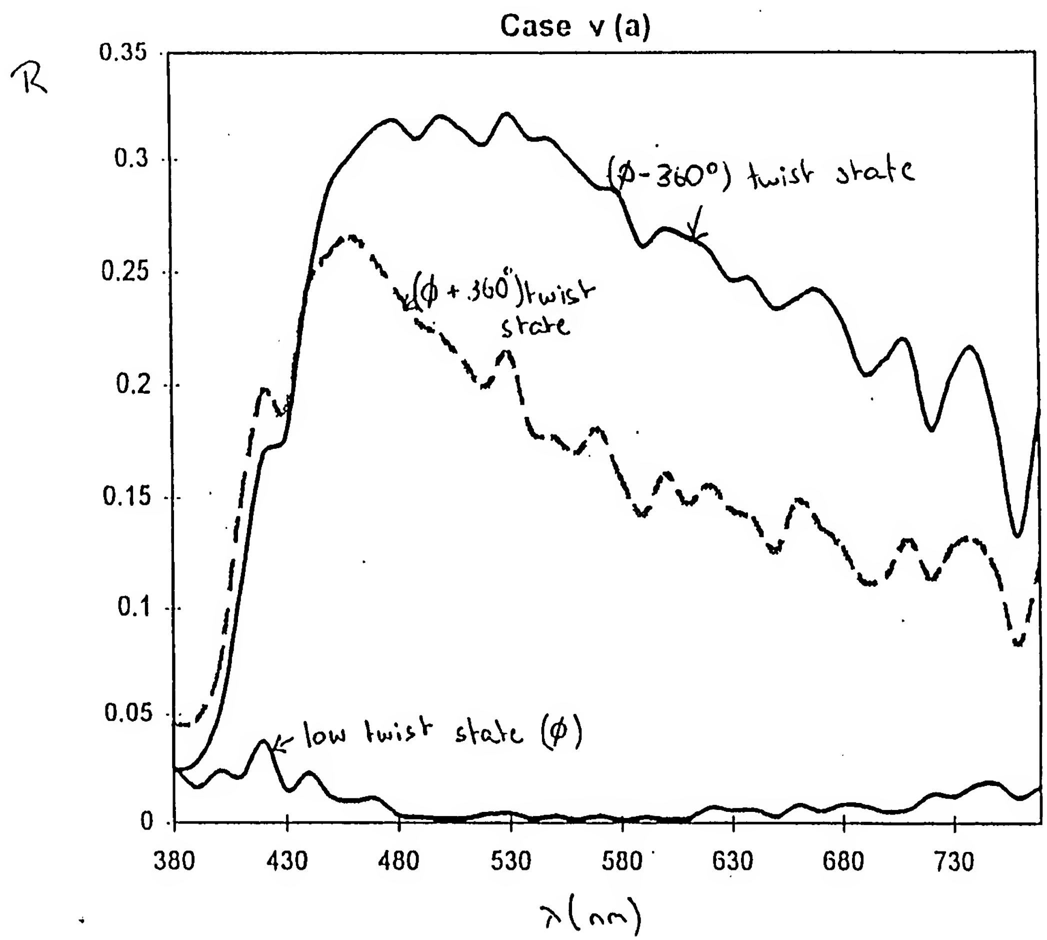

Case v (a)
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
λ(nm)
(φ-360°) twist state
(φ + 360°) twist state
low twist state (φ)

FIGURE 14

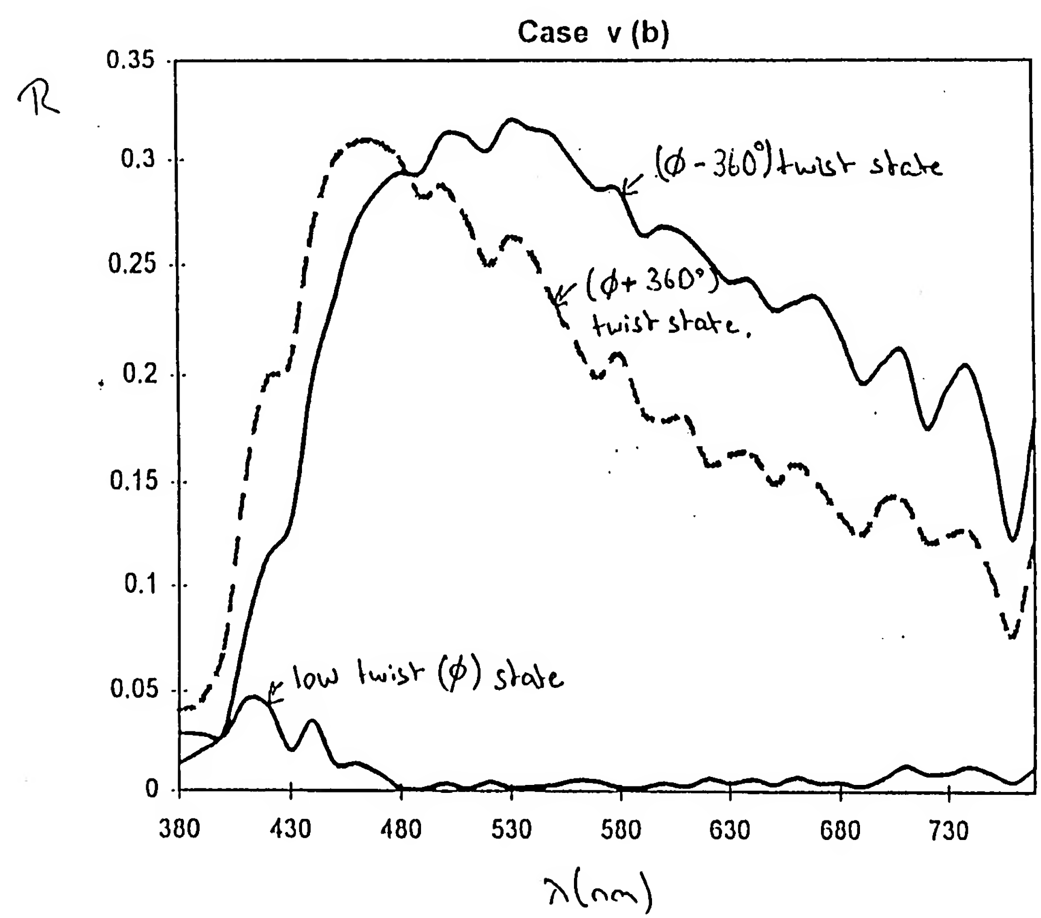
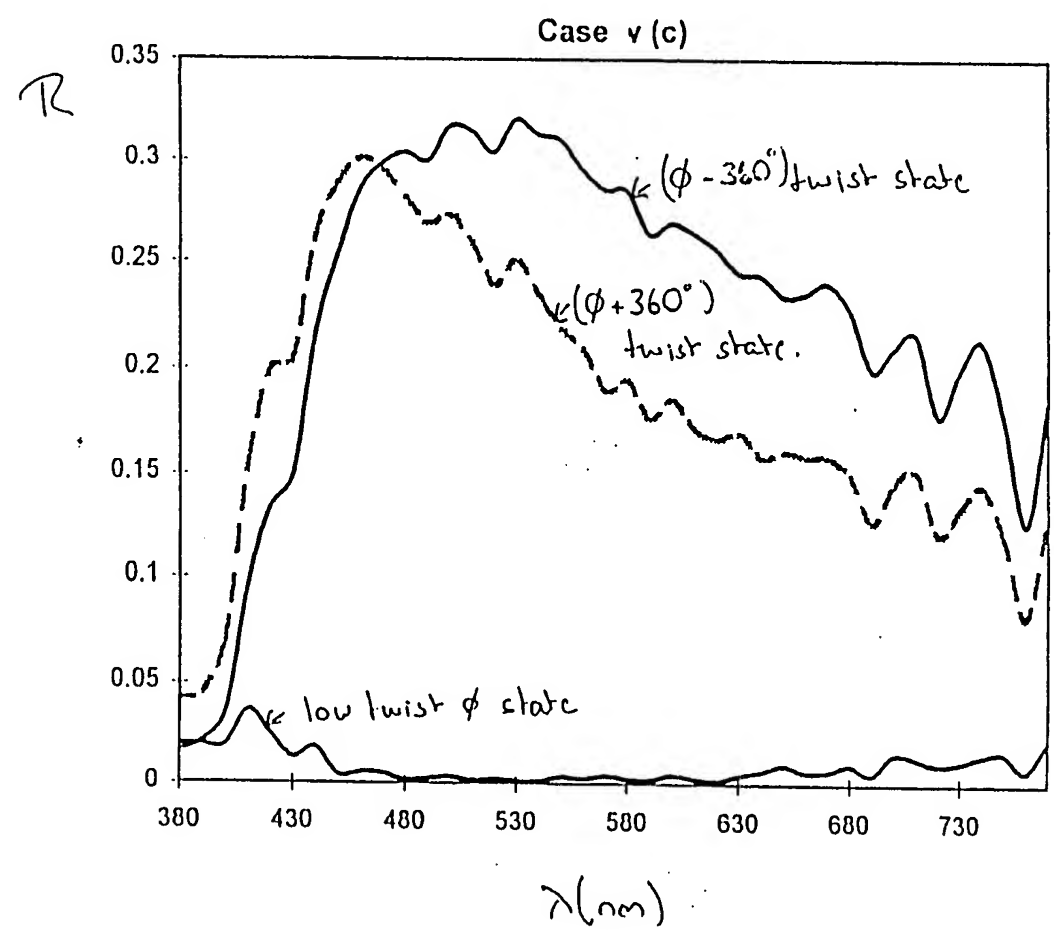
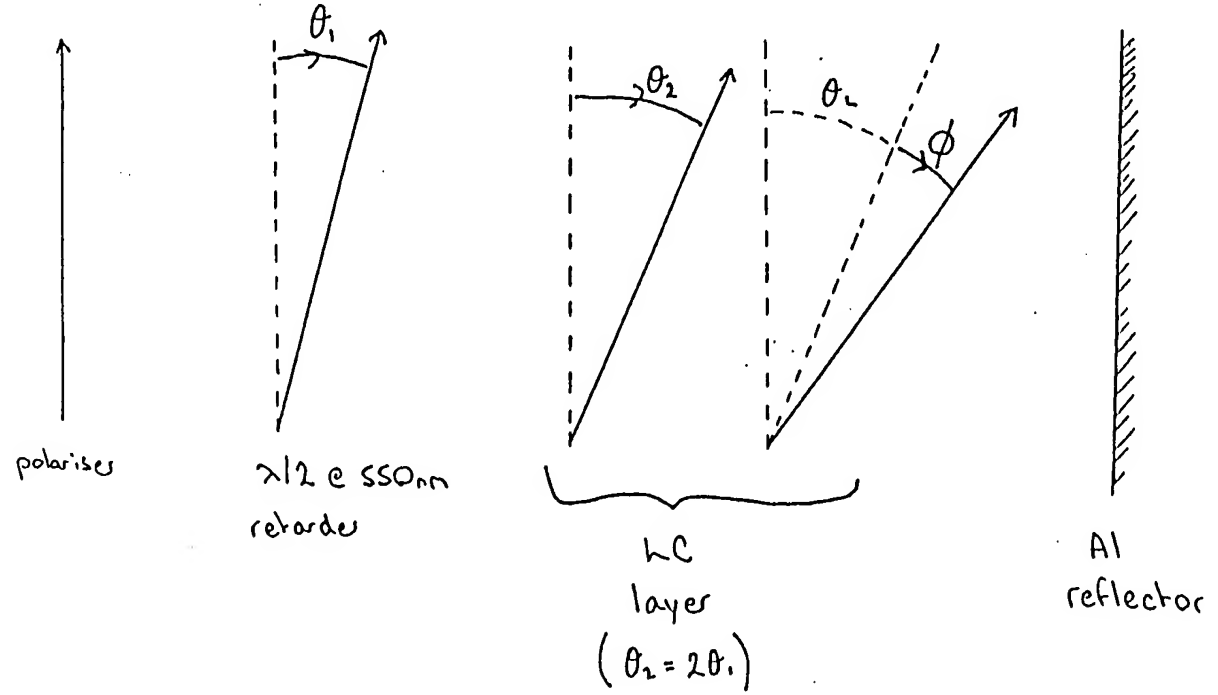

Case v (b)
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
λ(nm)
(ϕ - 360°) twist state
(ϕ + 360°) twist state.
low twist (ϕ) state

FIGURE 15



Case v (c)
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
380
430
480
530
580
630
680
730
λ(nm)
(φ - 360°) twist state
(φ + 360°) twist state.
low twist φ state

FIGURE 16



θ_1
θ_2
θ_2
ϕ
polarises
λ/2 @ 550nm
retarder
LC
layer
$(\theta_2 = 2\theta_1)$
Al
reflector

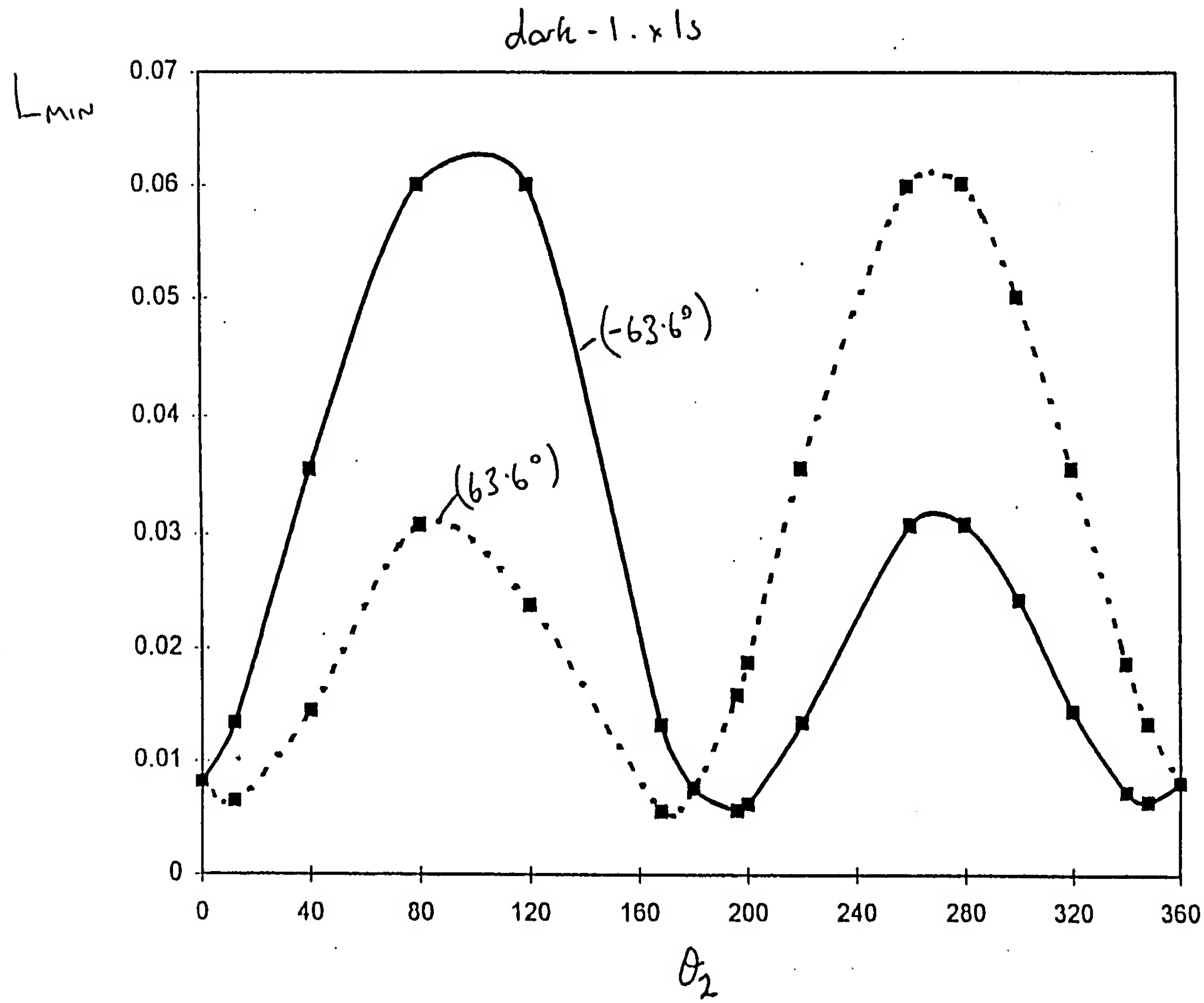

dark-1.xls
L_MIN
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
(-63.6°)
(63.6°)
0
40
80
120
160
200
240
280
320
360
θ2

FIGURE 17

FIGURE 18

2 layer - varying θ_1.

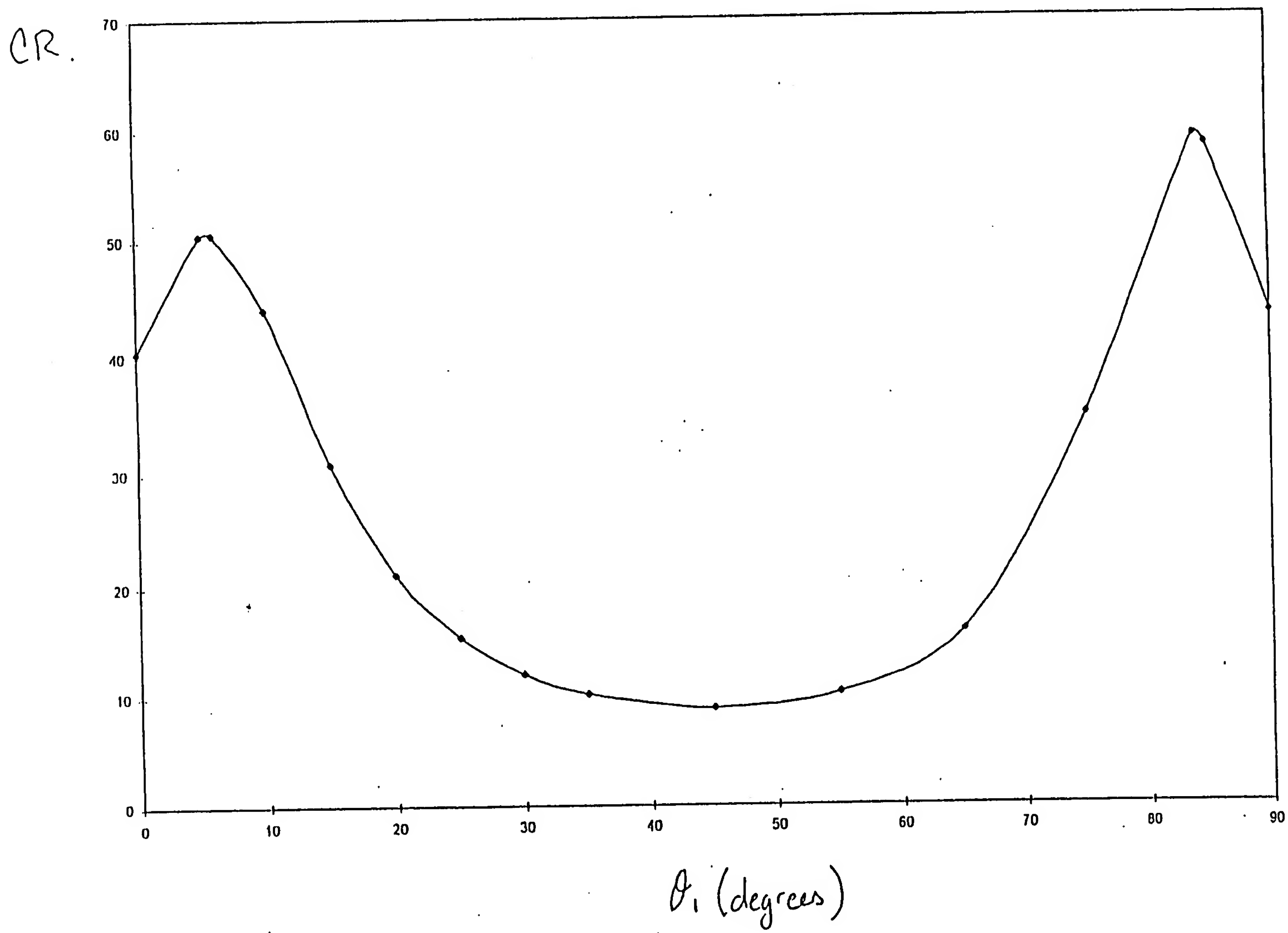
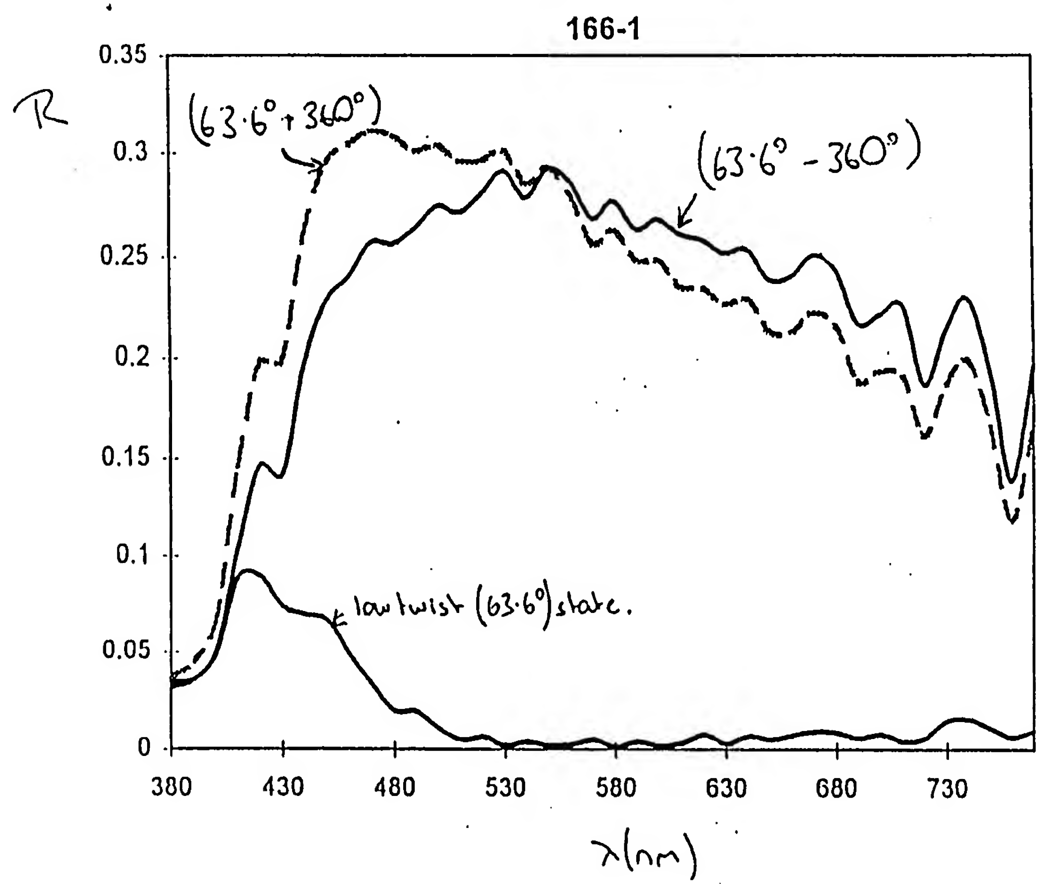


FIGURE 19

$\theta_1 = 6°$



$\theta_1 = 84°$

FIGURE 20

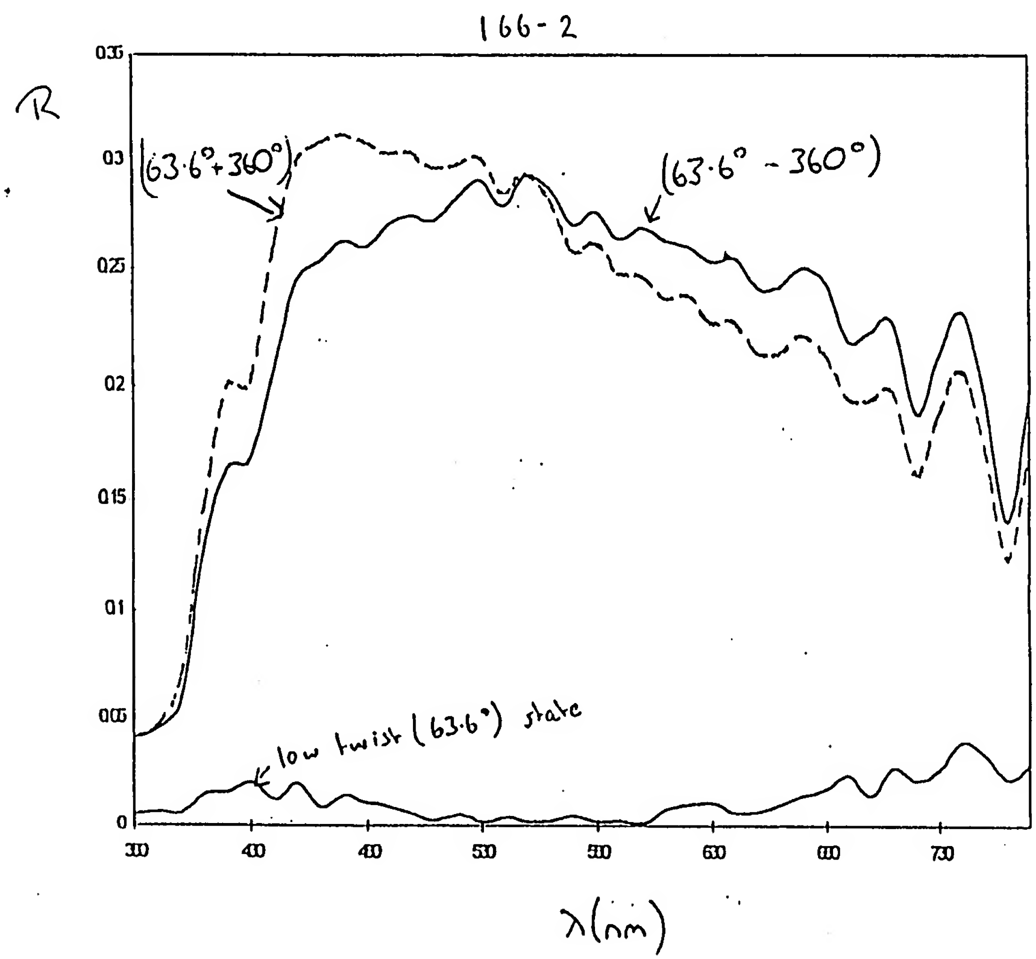
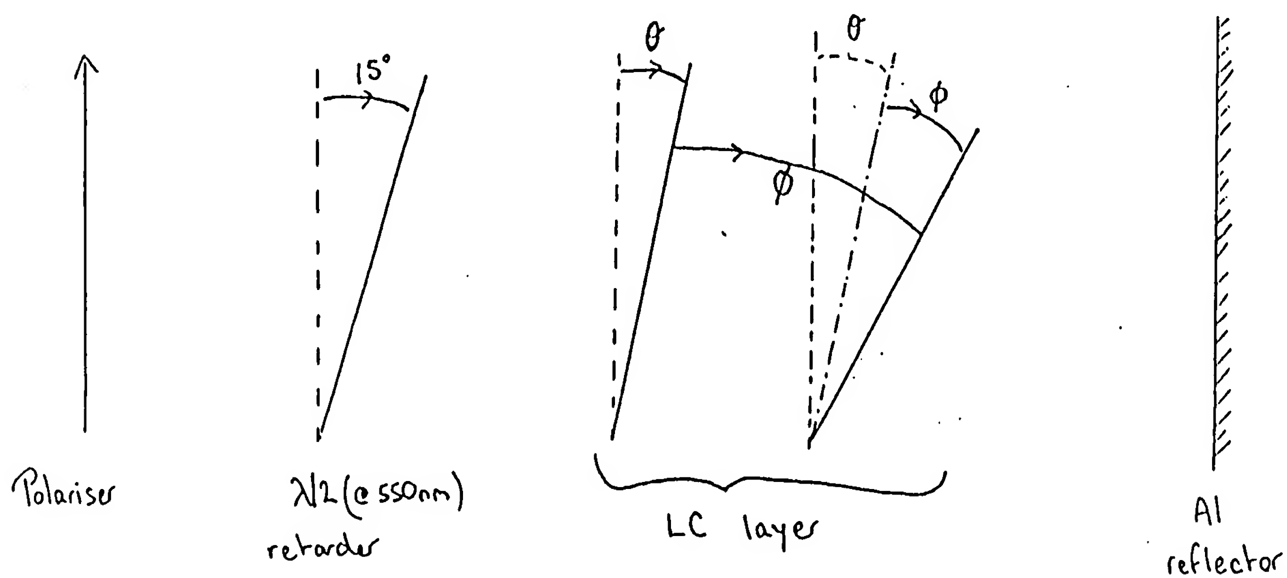


FIGURE 21



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	Twist of LC layer ϕ (degrees)	Input director of LC θ (degrees)	$\Delta nd/\lambda$ (λ=550nm)	Thickness of LC d (μm)
1	0	-45	.25	2.007
2	-11.4	-37.76	.252	2.023
3	-23.4	-30	.26	2.088
4	-36.7	-21.1	.275	2.208
5	-50.6	-11.1	.304	2.441
6	-63.6	0	.354	2.842
7	-70.1	8	.405	3.252
8	-72.5	15.2	.467	3.75
9	-69.9	21.78	.536	4.304
10	-65.5	25.66	.582	4.673
11	-58.1	29.6	.63	5.058
12	-50	32.7	.667	5.355
13	-38.4	36.2	.704	5.653
14	-25.1	39.5	.731	5.869
15	-12.1	42.4	.746	5.99
16	0	45	.75	6.022

Figure 22 Table of twisted LC configurations for which LC behaves equivalently to an untwisted ¼ wave plate, (θ = angle of the input director of LC with respect to the incident linear polarisation direction, ϕ = twist of LC layer, $\Delta nd/\lambda$ specifies the required $\Delta nd/\lambda$ for which the LC device behaves like a ¼ wave plate retarder).

FIGURE 22

FIGURE 23

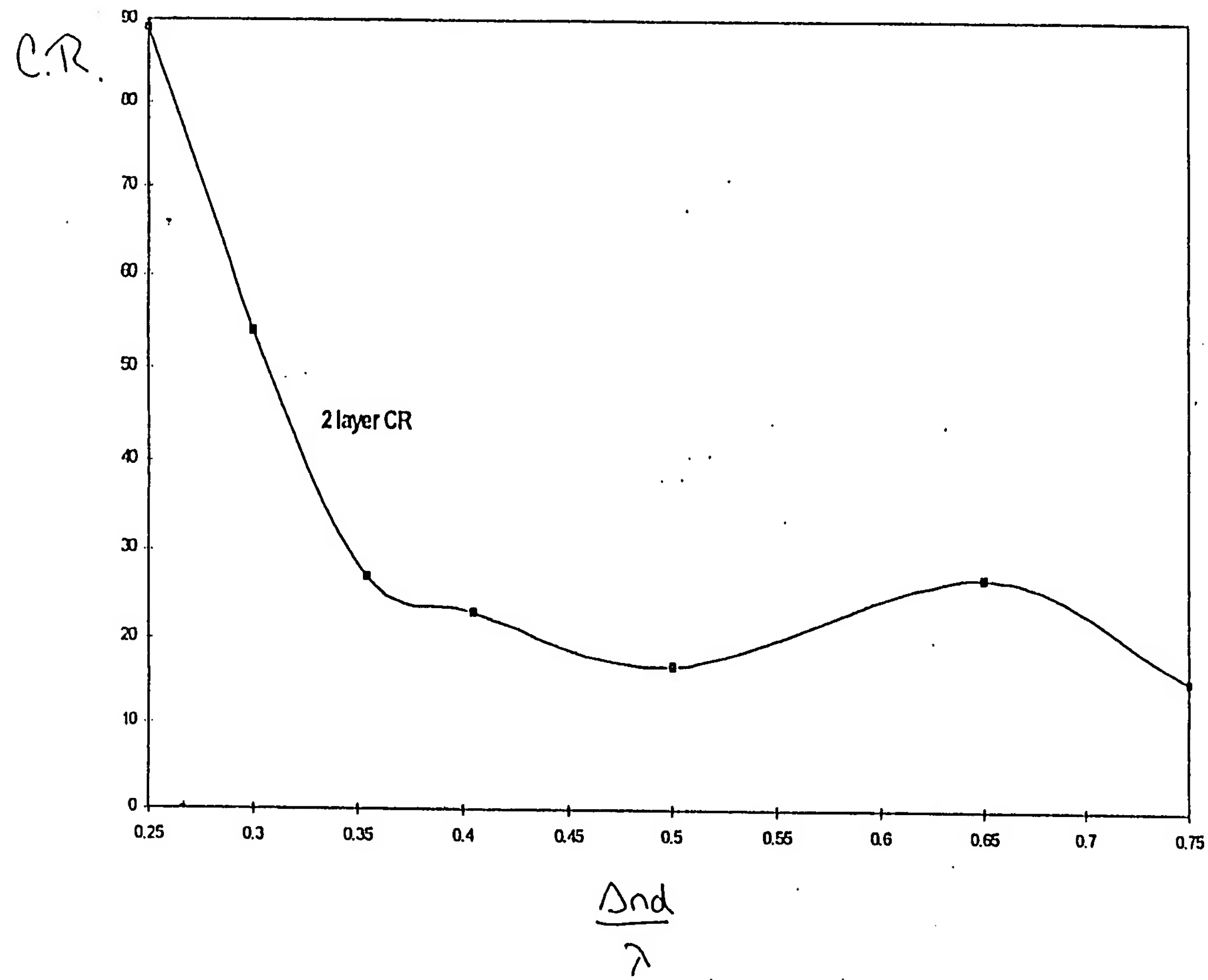
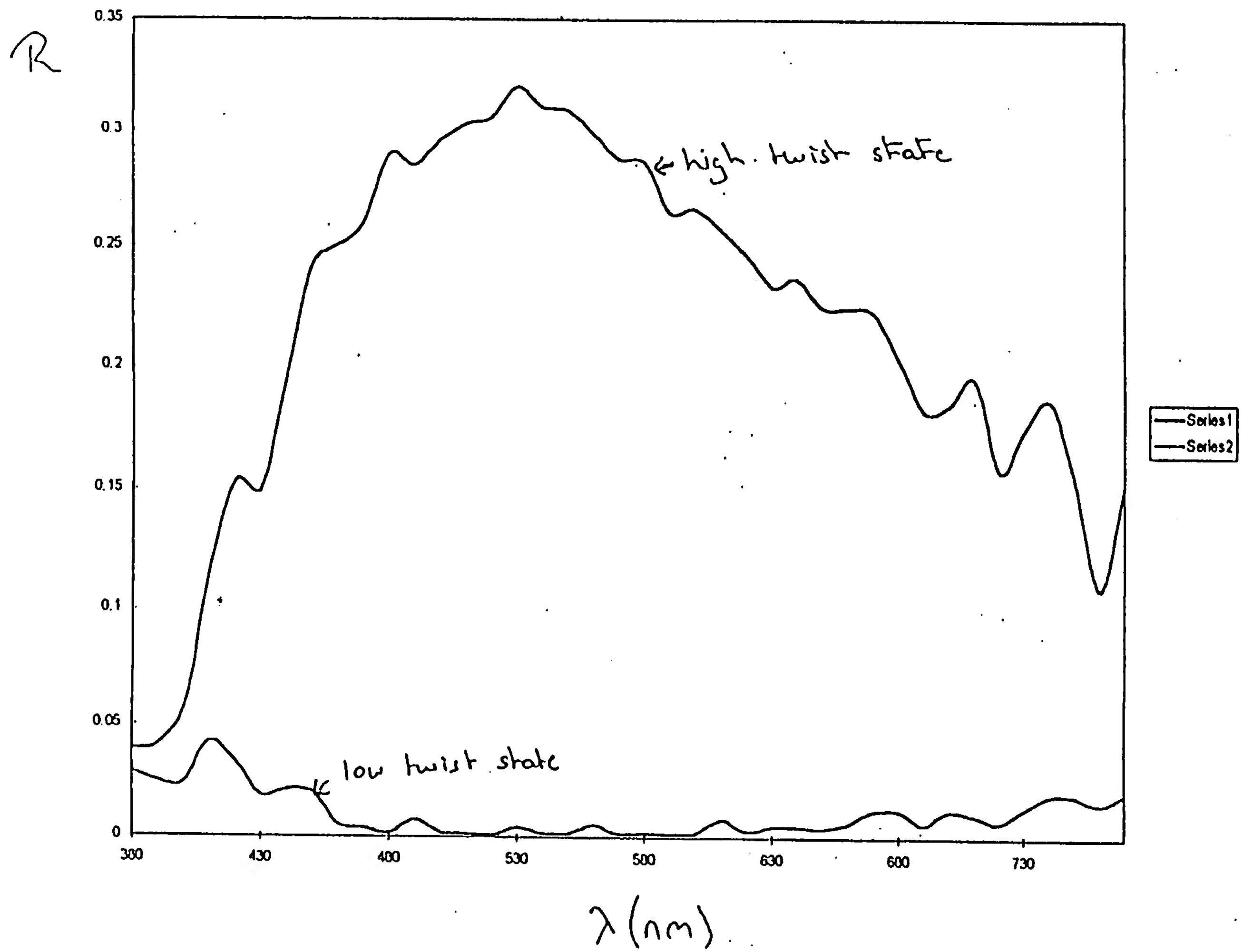

C.R.
90
80
70
60
50
40
30
20
10
0
2 layer CR
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
$\frac{\Delta nd}{\lambda}$

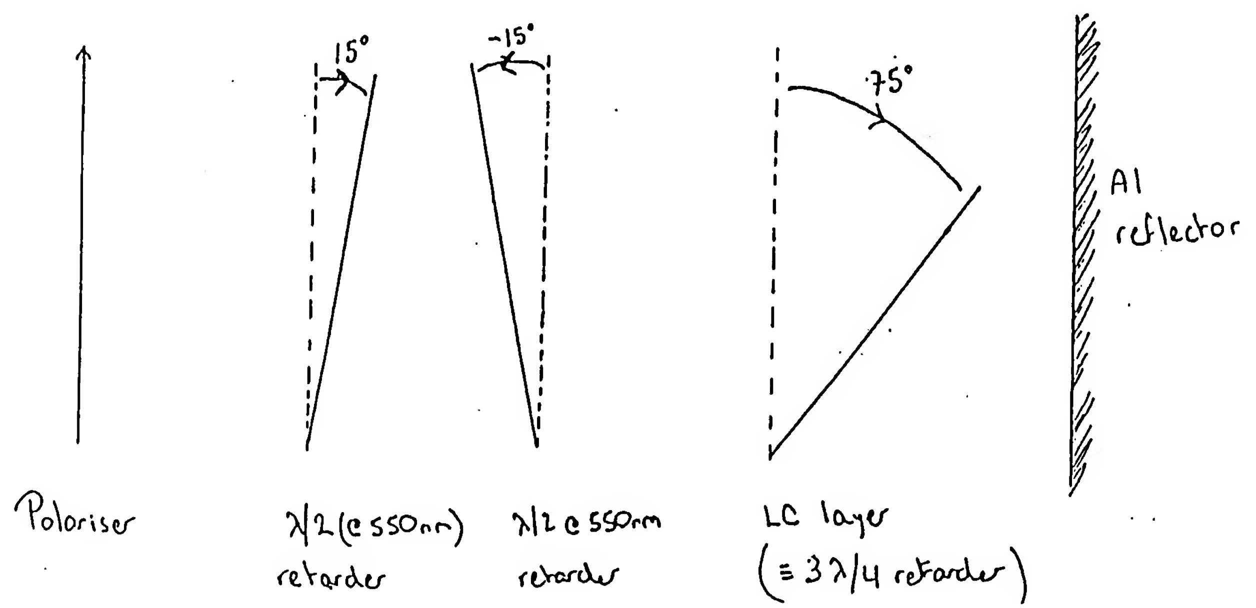
FIGURE 24

8-1



R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
300
430
400
530
500
630
600
730
← high. twist state
← low twist state
Series1
Series2
λ (nm)

FIGURE 25



Polariser
15°
λ/2 (@ 550nm)
retarder
-15°
λ/2 @ 550nm
retarder
75°
LC layer
(≡ 3λ/4 retarder)
Al
reflector

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(179-1)

FIGURE 26

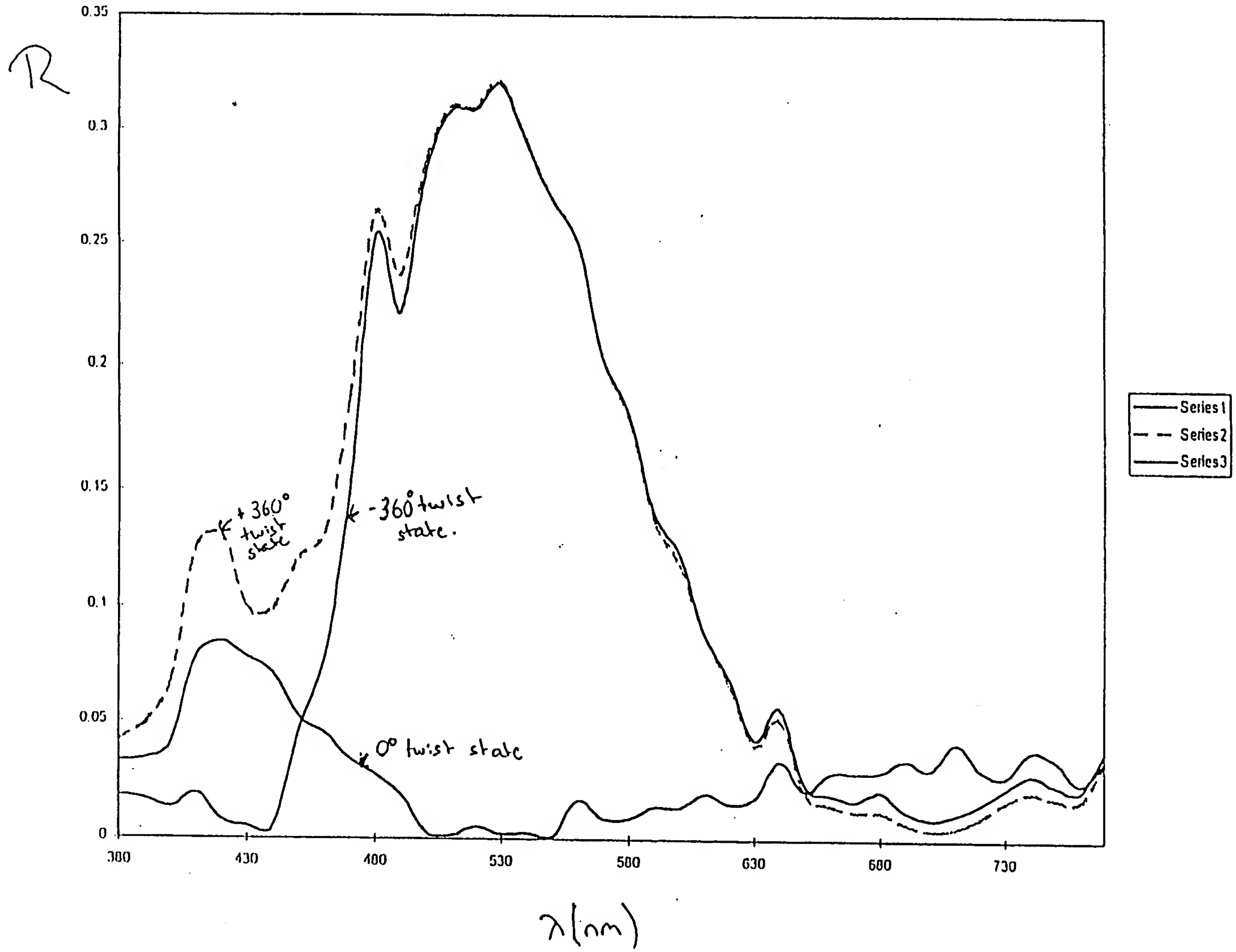


FIGURE 27

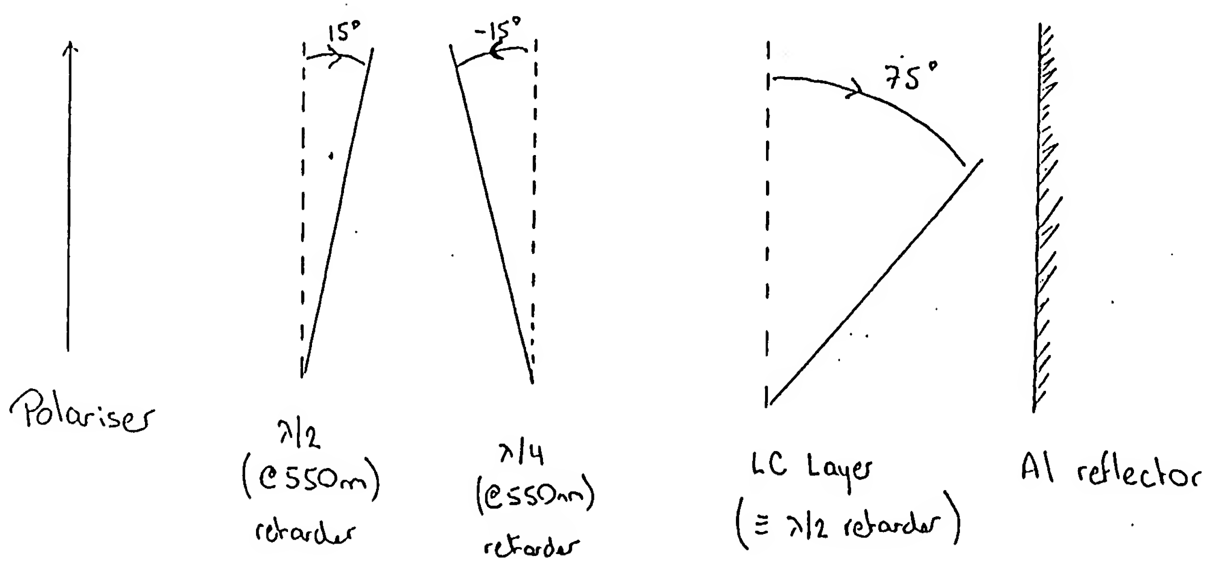
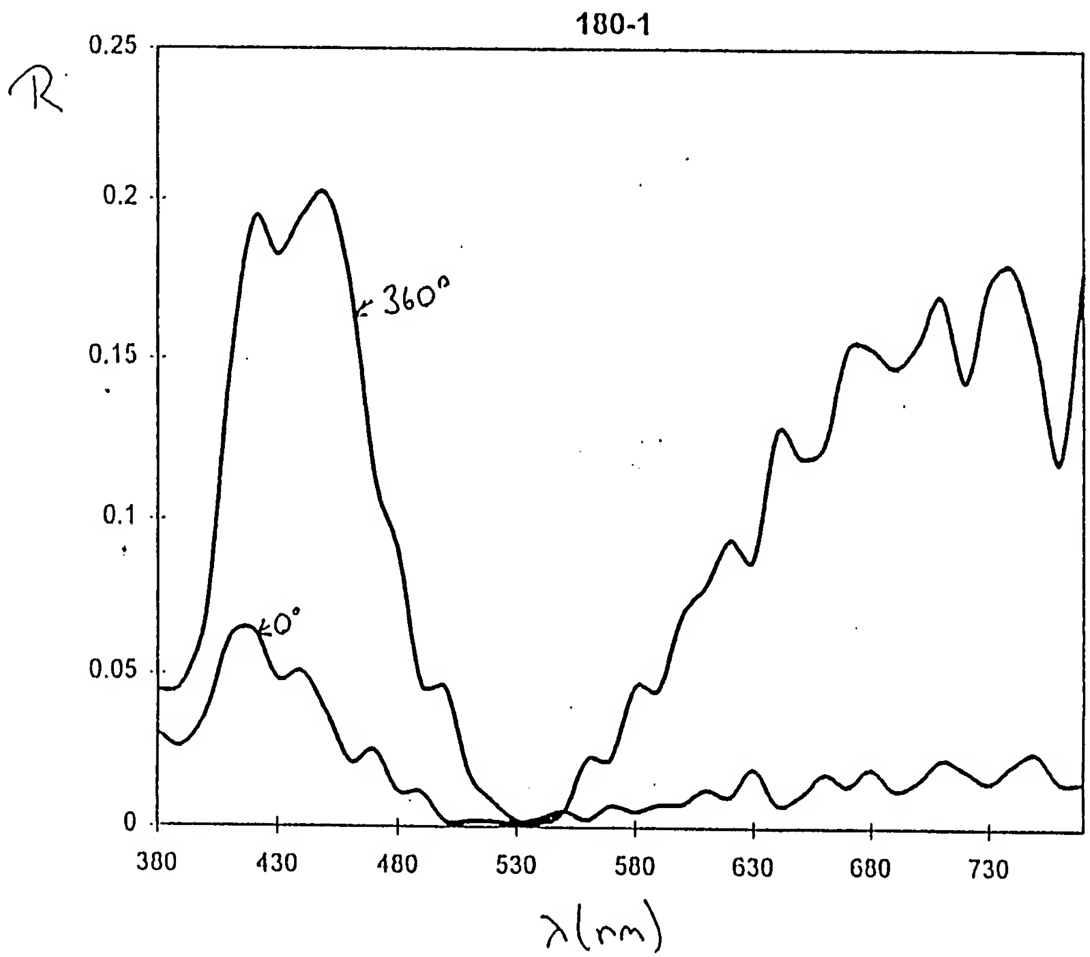
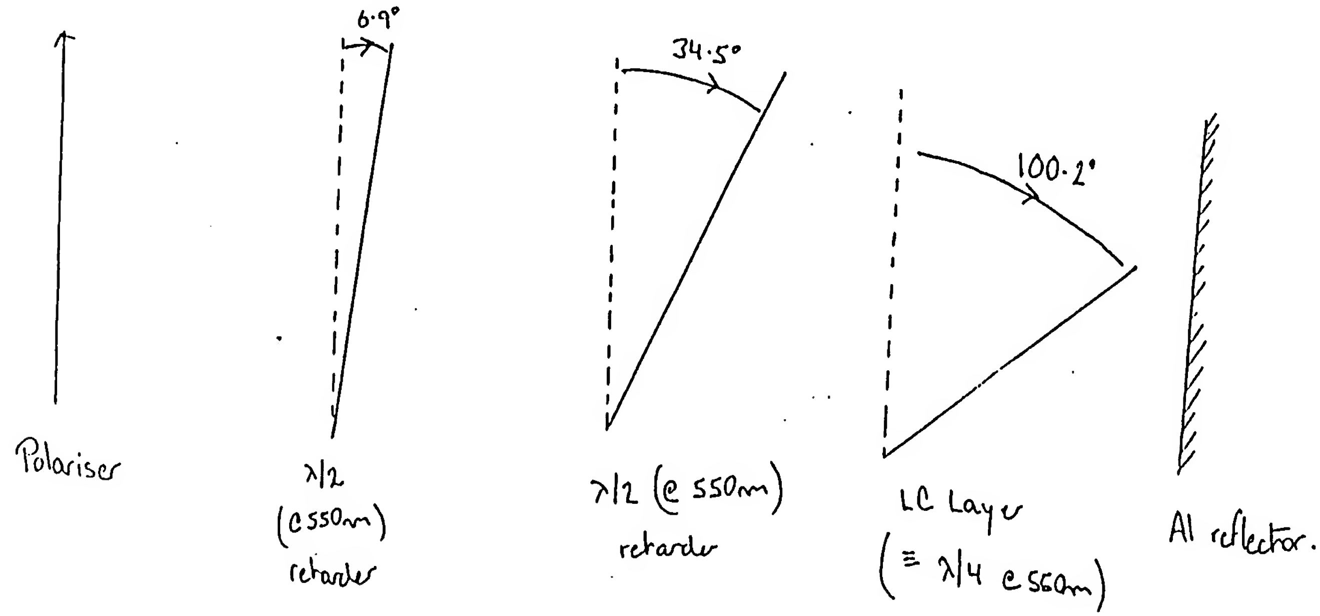

15°
-15°
75°
Polariser
λ/2
(@550m)
retarder
λ/4
(@550nm)
retarder
LC Layer
(≡ λ/2 retarder)
Al reflector

FIGURE 28



180-1
R
0.25
0.2
0.15
0.1
0.05
0
360°
0°
380
430
480
530
580
630
680
730
λ(nm)

FIGURE 29



6.9°
34.5°
100.2°
Polariser
λ/2
(@550nm)
retarder
λ/2 (@ 550nm)
retarder
LC Layer
(≡ λ/4 @ 550nm)
Al reflector.

(160-1)

FIGURE 30

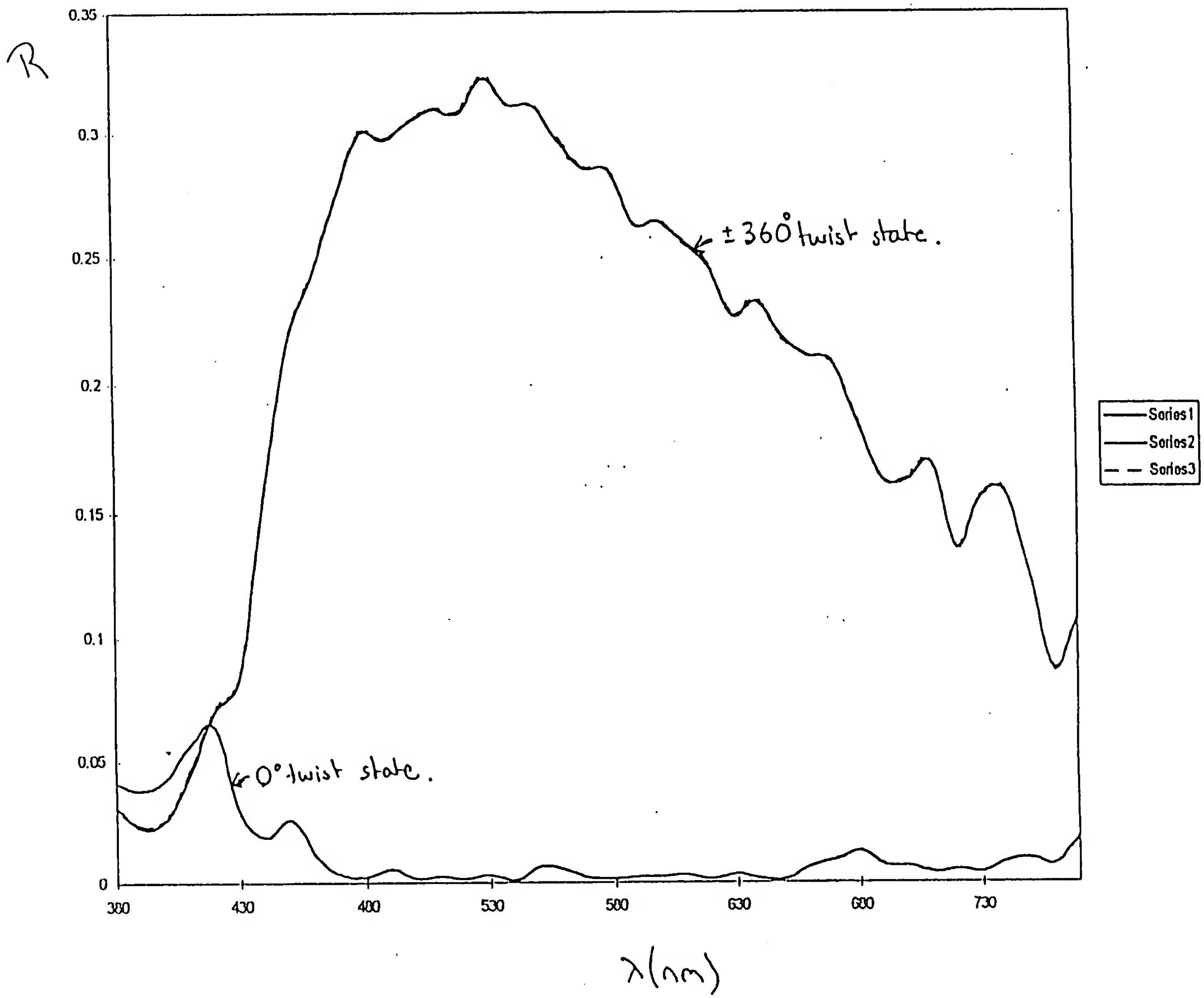
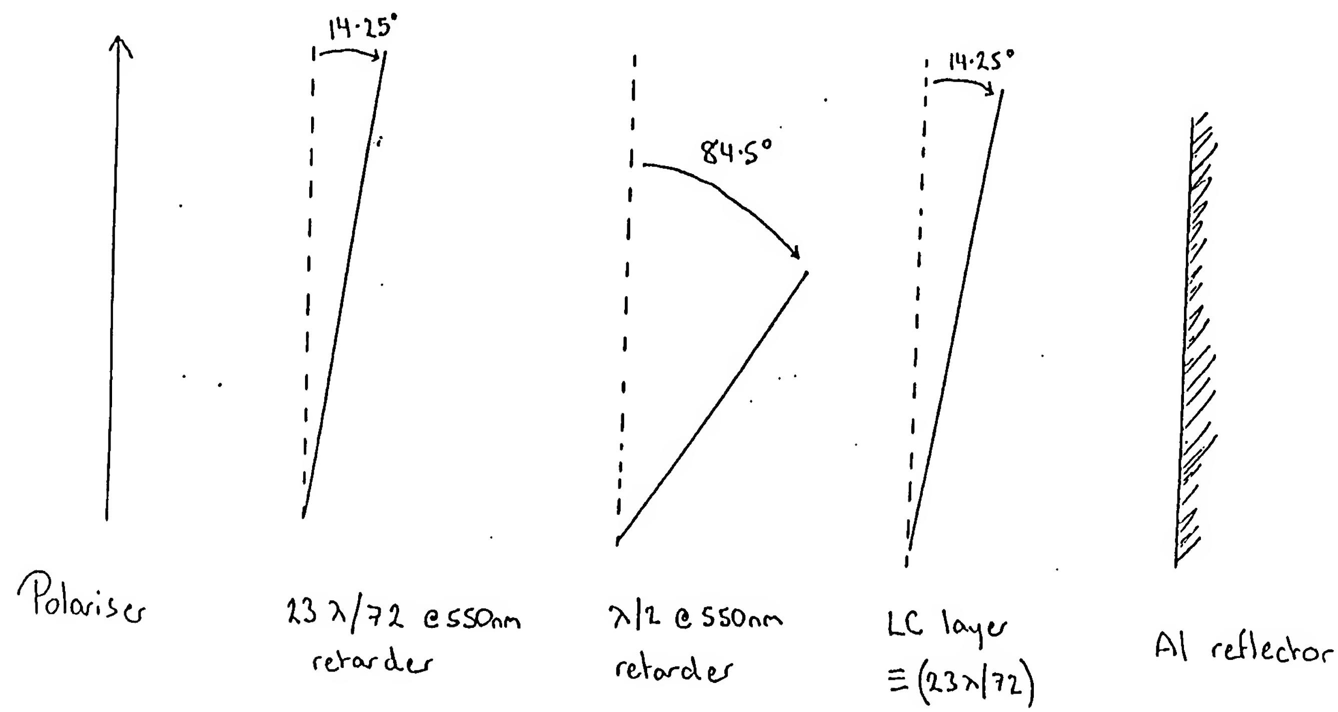


FIGURE 31



14·25°
84·5°
14·25°
Polariser
23 λ/72 @ 550nm retarder
λ/2 @ 550nm retarder
LC layer ≡ (23λ/72)
Al reflector

FIGURE 32

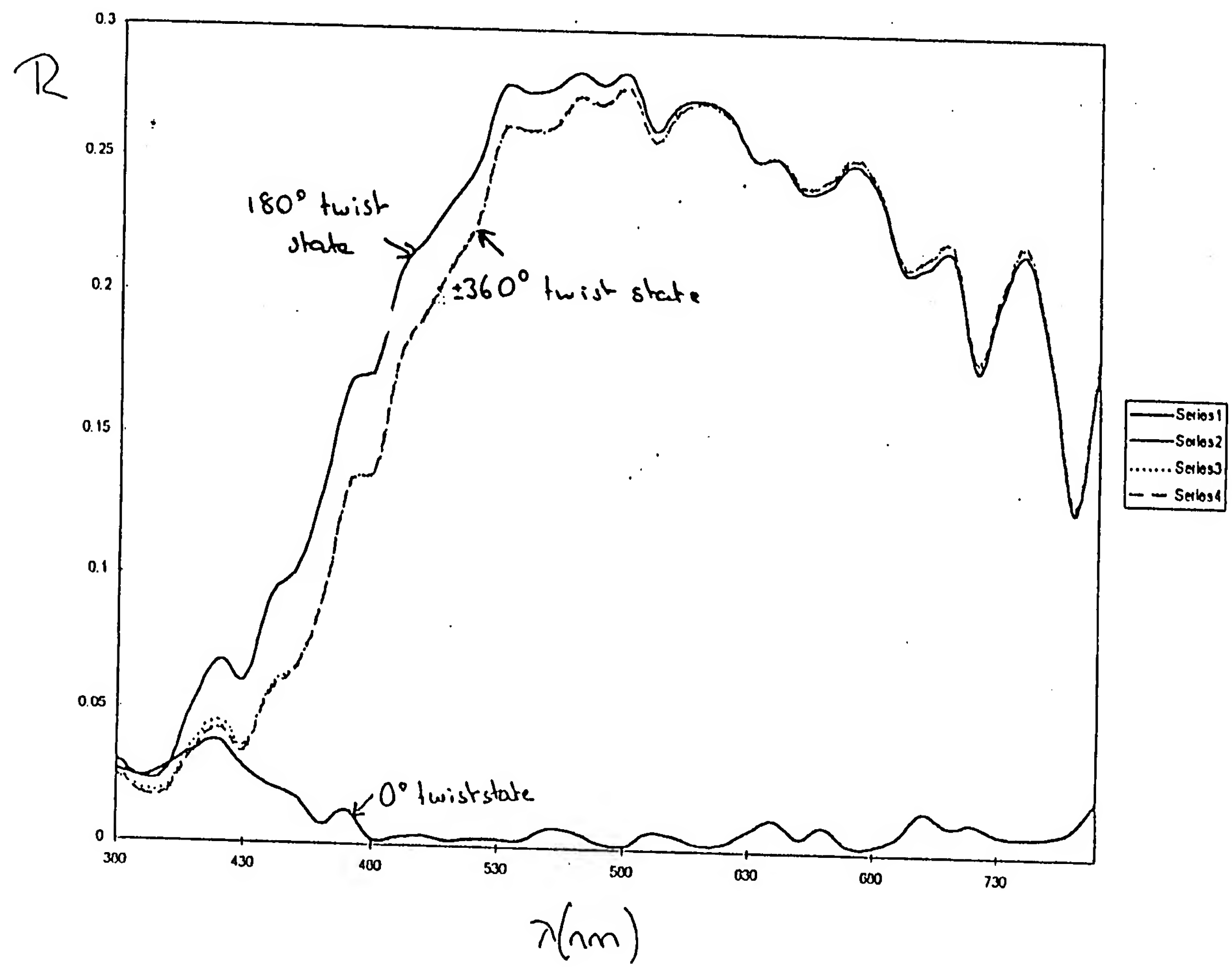
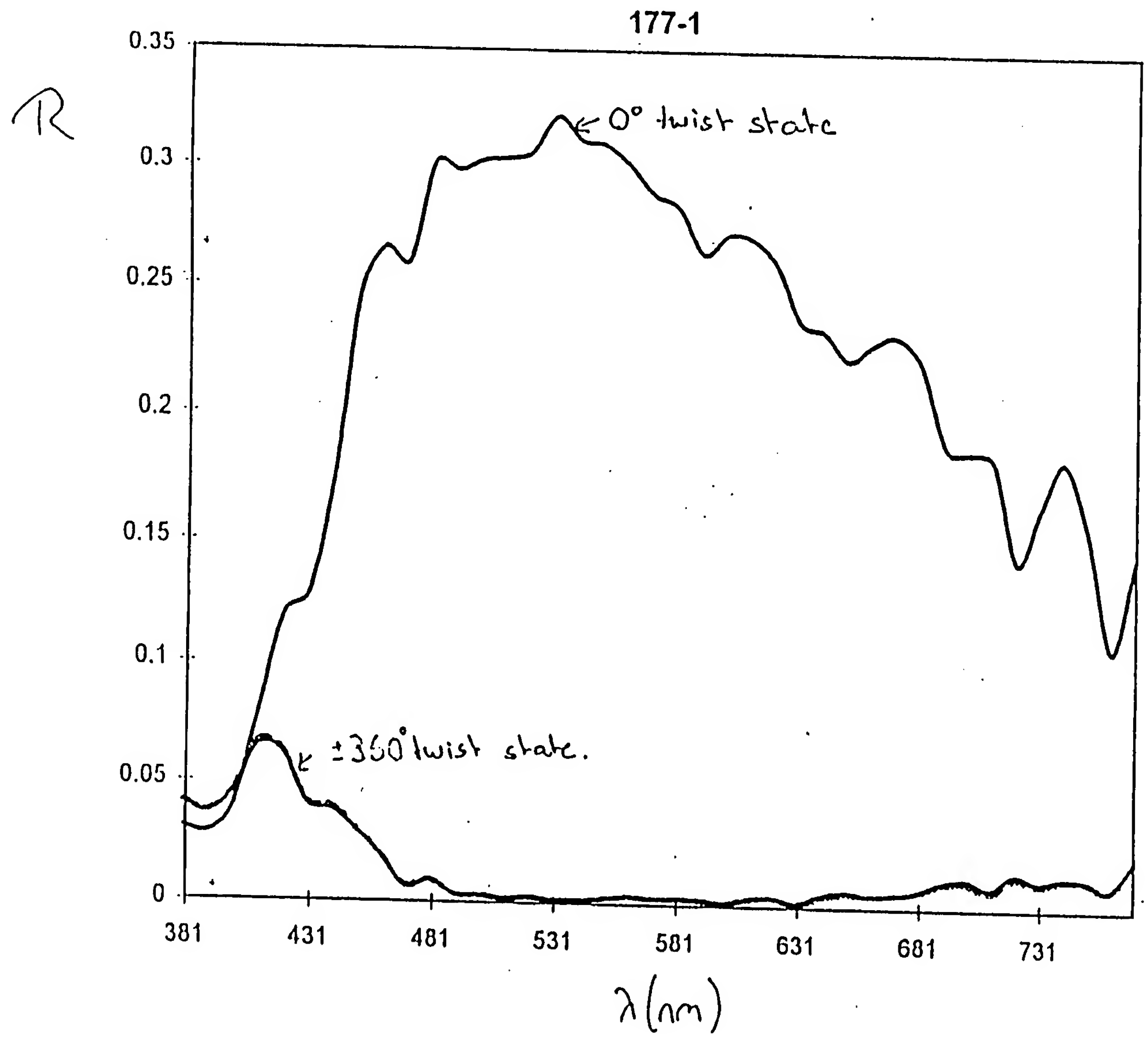

R
0.3
0.25
0.2
0.15
0.1
0.05
0
300
430
400
530
500
030
600
730
λ(nm)
180° twist state
±360° twist state
0° twiststate
Series1
Series2
Series3
Series4

FIGURE 33



177-1
R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
381
431
481
531
581
631
681
731
λ(nm)
0° twist state
±360° twist state.

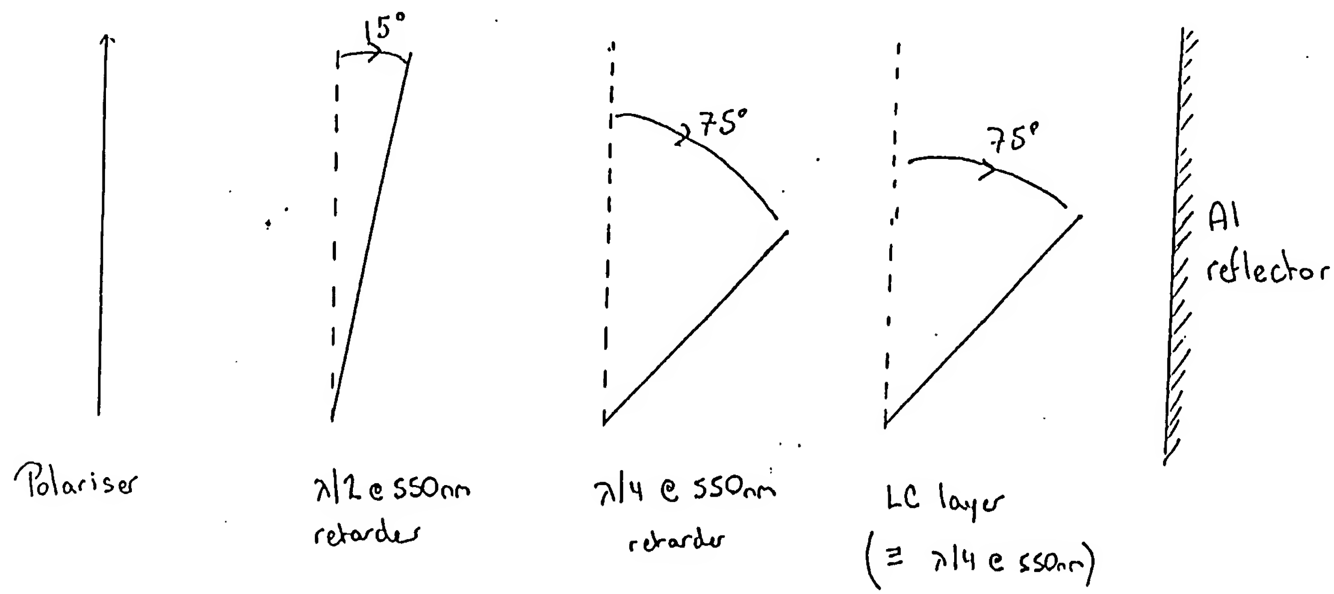

15°
75°
75°
Al
reflector
Polariser
λ/2 @ 550nm
retarder
λ/4 @ 550nm
retarder
LC layer
(≡ λ/4 @ 550nm)

FIGURE 34

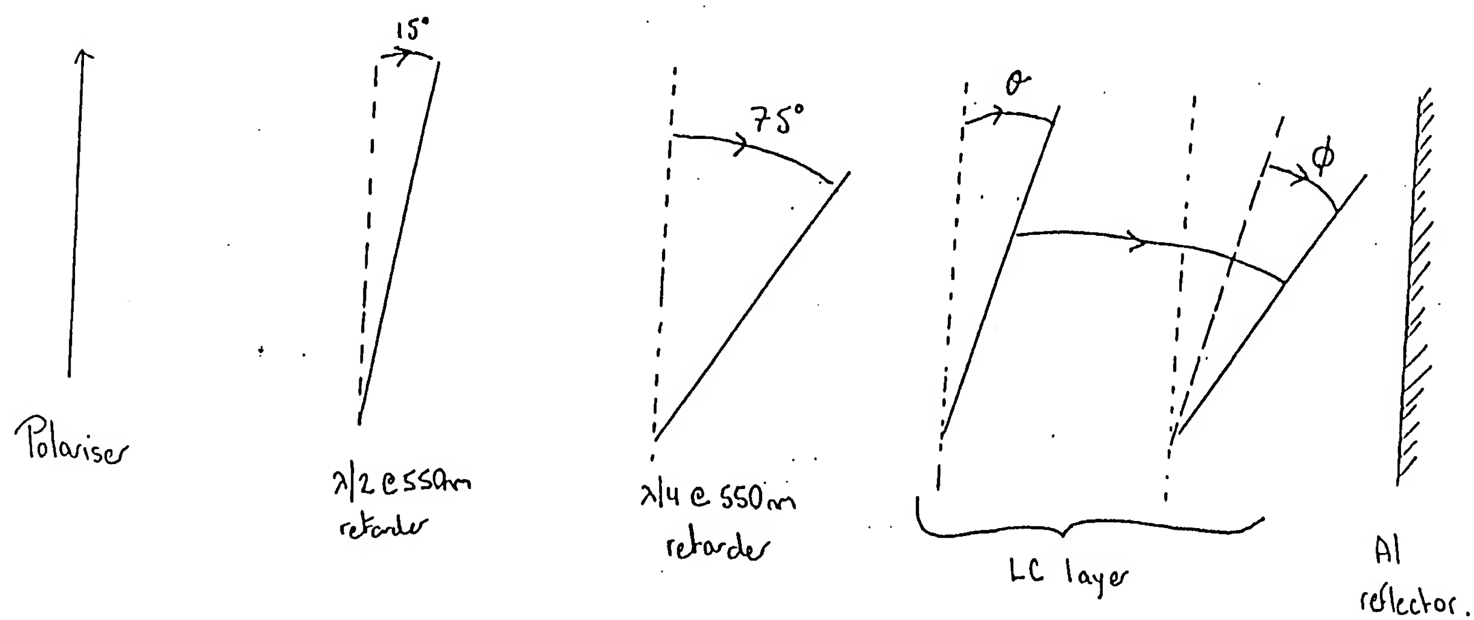
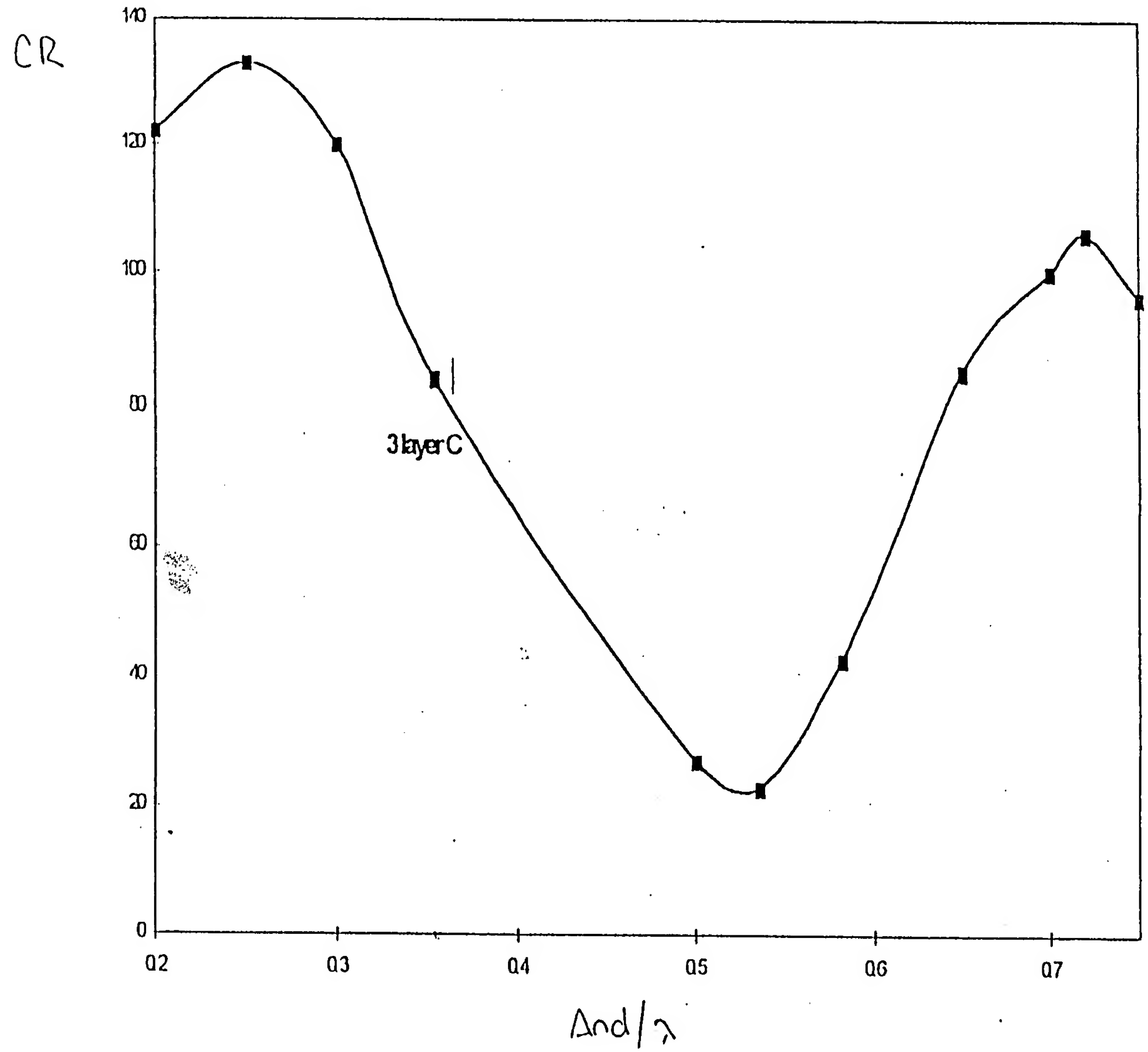

15°
75°
θ
φ
Polariser
λ/2 @ 550nm
retarder
λ/4 @ 550nm
retarder
LC layer
Al
reflector.

FIGURE 35

FIGURE 36



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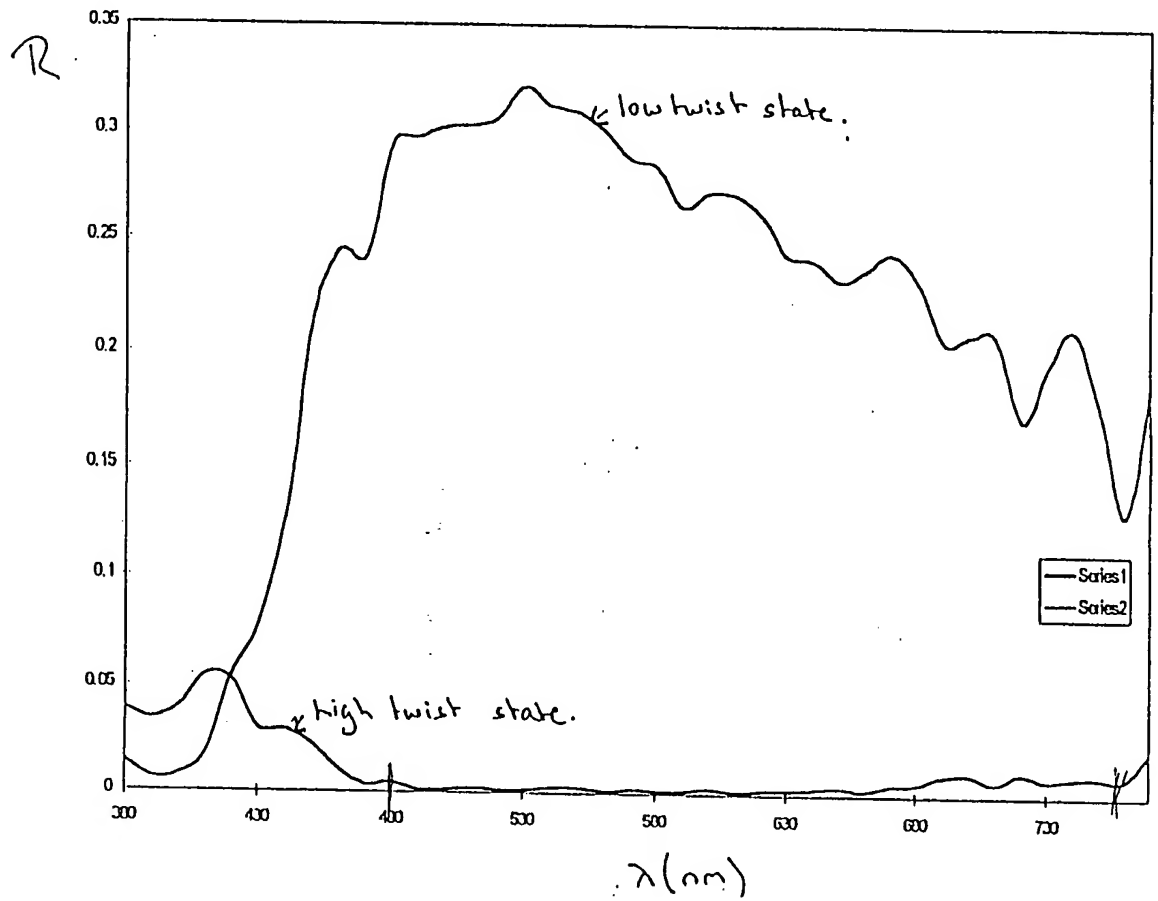
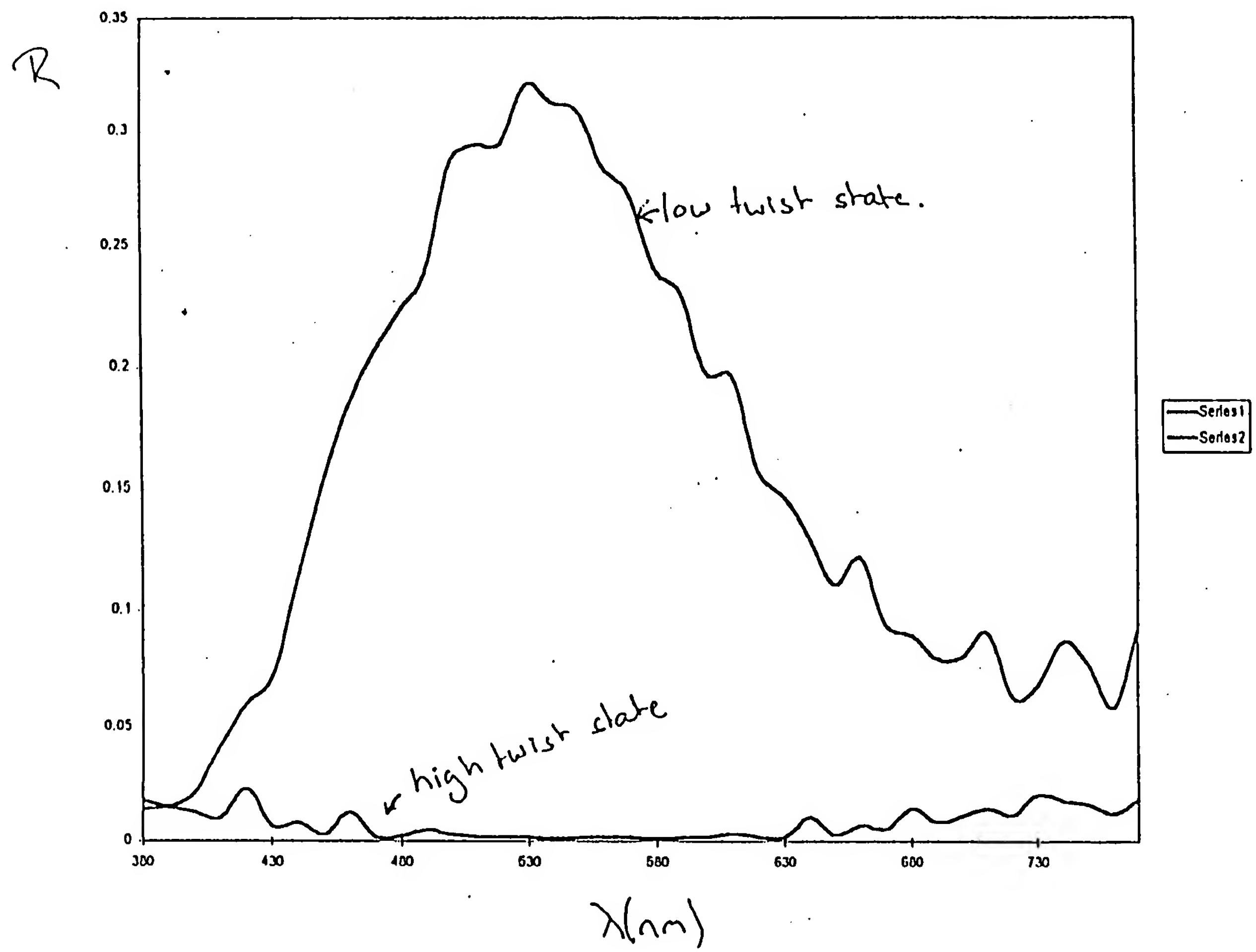
(136-2)

FIGURE 37



(6)

FIGURE 38



R
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
300
430
480
530
580
630
680
730
λ(nm)
low twist state.
high twist state
Series1
Series2

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(138-1) FIGURE 39